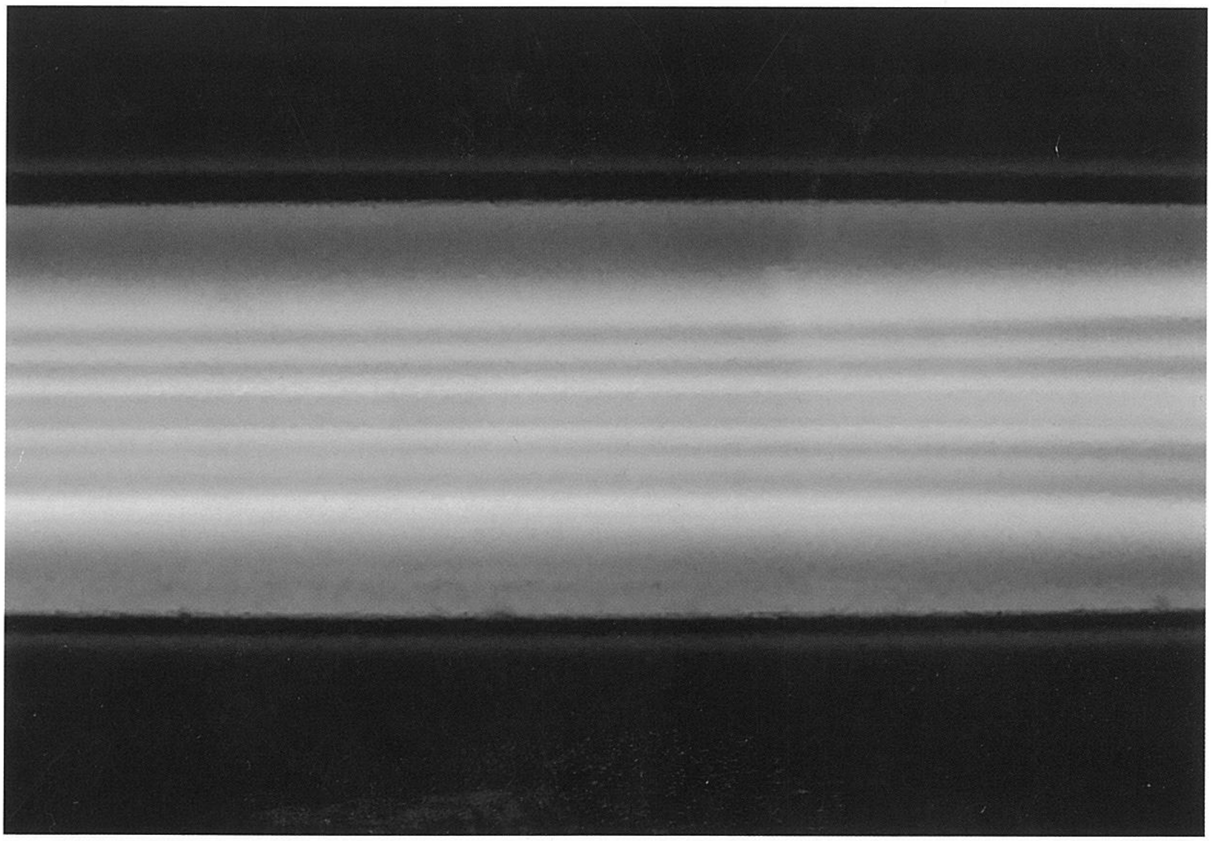
BULLETIN

OF THE AMERICAN PHYSICAL SOCIETY

70th Annual Gaseous Electronics Conference

November 6-10, 2017
Pittsburgh, PA



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APS physics

BULLETIN

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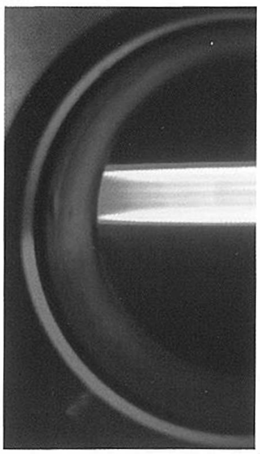
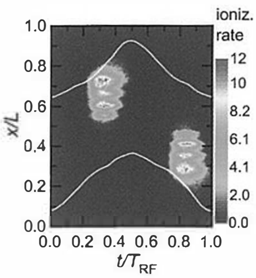


Striations in an electronegative capacitive radio frequency discharge induced by a resonance of the externally applied voltage waveform and the ion-ion plasma: experimental observation and simulation results



Courtesy of Y. X. Liu, E. Schuengel, I. Korolov, Z. Donko, Y.-N. Wang, and J. Schulze Phys. Rev. Lett. 116, 255002 (2016).

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70th Annual Gaseous Electronics Conference

Table of Contents

70th Annual Gaseous Electronics Conference

November 6-10, 2017
Pittsburgh, PA

WELCOME TO PITTSBURGH! – GENERAL INFORMATION

Pittsburgh's multiple universities and established cultural institutions (e.g., Carnegie Museum of Natural History, the Carnegie Museum of Art, and the Phipps Conservatory and Botanical Gardens) lie on the Allegheny Plateau, where Ohio, Monongahela, and Allegheny Rivers join, festooned with 446 bridges. Pittsburgh, a thriving steel city in the 20th century and a hub of technology and innovation now, is surrounded by wooded hills of the Appalachian Mountains. In the "North Shore" neighborhood we find the iconic Andy Warhol Museum, Heinz Field football stadium and PNC Park baseball stadium.

West Virginia University, in nearby Morgantown, one hour away, welcomes you to GEC 2017 and invites you to become more familiar, at *about.wvu.edu*, with the institution's pioneering, passionate, innovative, tireless, and caring spirit.

WVU researchers developed the world's first fully transportable heavy-duty vehicle emissions testing laboratory. In 2015, the Environmental Protection Agency credited a 2014 WVU study for raising questions about real-world emissions levels in Volkswagen light-duty diesel engines. Dan Carder, the WVU engineer who led the research team, was named to the 2016 *Time* 100, the magazine's annual list of the 100 most influential people in the world.

Decades before the nation went "green", WVU launched one of the country's only eco-efficient people movers – the Personal Rapid Transit, or "PRT." It's the only system in the world that allows riders to travel point to point without stopping at another station.

WVU was the first in the U.S. to train miners and houses one of the world's largest simulated underground coal mines. Building on its heritage of energy research, WVU is fostering the responsible use of fossil energy and the development of sustainable energy technologies. Initiatives like EcoCAR are inspiring a new generation of leaders.

LAUNCH YOUR GEC WEEK WHILE IMMERSED IN A THEME – PRE-CONFERENCE WORKSHOPS

Monday includes four half-day preconference workshops. The session code is translated according to 1 = Salon D of Grand Ballroom, 2 = Duquesne Room, and 4 = Duquesne Room, with M for Monday and A = "9:00am to 12:30pm" and B = "2:00pm to 5:30pm".

SESSION AM1 (9-12:30):
"Linking academia and industry"
Salon D of Grand Ballroom

SESSION BM1 (2-5:30):
"Practical challenges for industry"
Salon D of Grand Ballroom

SESSION AM4 (9-12:30):
"Scientific paper writing workshop"
Foster Room

SESSION BM2 (2-5:30):
"Linking theory and experiment"
Duquesne Room

LET THE TECHNICAL PROGRAM FASCINATE YOU – SPECIAL SESSIONS AND EVENTS

The Gaseous Electronics Conference (GEC) is a special conference of the American Physical Society (APS) Division of Atomic, Molecular and Optical Physics (DAMOP). GEC promotes ideas on the physical and chemical processes and dynamics taking place in partially ionized, collisional plasma and between the atoms, molecules, charged particles, photons, waves, and fields.

GEC has been an invaluable resource to the plasma and collision community, and continues to have a leadership presence in traditional areas such as plasma phenomena, low-pressure processes, plasma chemistry, surface interactions, atomic and molecular interactions, simulation, and diagnostics. In recent years, the GEC has also taken a leadership role in biological and environmental applications and atmospheric plasma systems, some of the hottest emerging areas of plasma science.

The conference will bring together over 400 scientists and engineers from around the world who will attend 31 invited talks, over 175 oral contributed talks, and over 180 poster presentations. The technical program includes the Will Allis Prize talk on Wednesday morning, one evening discussion group on Wednesday, and a federal agency session on Thursday morning. One student will receive the "Student Award for Excellence" for excelling among six oral-presentation finalists. The social program includes a welcome reception Monday evening and a Thursday evening conference dinner with a pre-dinner reception.

A MUST-SEE PRESENTATION – WILL ALLIS PRIZE TALK, WEDNESDAY, NOV 8, 10AM

Will Allis Prize Speaker: Prof. Klaus Bartschat, Department of Physics and Astronomy, Drake University, Des Moines IA, 50311, USA

The GEC Executive Committee is pleased to recognize Klaus Bartschat, from Drake University, as the recipient of the 2016 Will Allis Prize for the Study of Ionized Gases. His talk entitled *Electron Collisions–Experiment, Theory, and Applications* will start at 10:00 AM on Wednesday, November 8, in Salons DE. https://www.aps.org/programs/honors/prizes/allis.cfm

The Will Allis Prize was established in 1989 by contributions from American Telephone and Telegraph, General Electric, General Telephone and Electronics, International Business Machines, and Xerox Corporations in recognition of the outstanding contributions of Will Allis to the study of ionized gases.

LET'S BUILD TOGETHER! – LXCAT DISCUSSION ON WEDNESDAY, NOVEMBER 8

LXCat (www.lxcat.net) is an open-access, web-based platform for storing, exchanging, and manipulating data needed for the electron and ion components in low-temperature, non-equilibrium plasma. Over 40 physicists from institutions around the world have contributed to the 24 public databases representing this project, and the data are widely used by members of the GEC community. The database contributors retain ownership and are responsible for the contents and maintenance of the individual databases. New contributors are welcome, can request an account, and will receive instructions for setting up a password-protected database on LXCat.

An informal meeting to discuss questions, suggestions and plans for the LXCat project will be held on Wednesday, November 8 from 7:00-9:00pm. If you are a current/future user or contributor, or if you are simply interested in knowing more about the project, please plan to attend. For further information or to suggest agenda items please contact Larry Viehland at viehland@chatham.edu. The discussion group will be in the Duquesne Room.

LET'S FIGURE IT OUT – SESSION-NUMBER SCHEME

Each session has a code consisting of three characters (two letters and a number). The first letter follows the sequence of 23 unique session start times from A through W. The second letter indicates the day of the week: T for Tuesday, W for Wednesday, R for Thursday, and F for Friday. The number indicates the room location. The numbering scheme is driven by the requirements of the APS meeting database system.

Letter:

1st = Chronological Designation (examples)	*2nd = Day of the Week*	*3rd = Room Location*
G = Tuesday 16:00 Posters	T = Tuesday	1 = Salon D
N = Wednesday 16:00 Posters	W = Wednesday	2 = Duquesne
T = Thursday 16:00 Orals	R = Thursday	3 = Oakmont Junior Ballroom
	F = Friday	4 = Foster

PLAN AHEAD – PRESENTATION FORMAT

Papers that have been accepted for presentations are listed in the scientific program. Invited talks are allotted 25 minutes, with 5 additional minutes for questions and discussion. Contributed talks are allotted 12 minutes, with 3 additional minutes for questions and discussion. Double-sided poster boards in Salons ABC measure 4 feet (1.3 m) high by 8 feet (2.6 m) wide. Each poster presentation lasts 2 hours (Tuesday or Wednesday 4-6 pm), but posters may be displayed throughout the day, and must be removed within 30 minutes of the close of its poster session.

LET'S CONGRATULATE! – GEC STUDENT AWARD FOR EXCELLENCE

The GEC Executive Committee will present one student award (US$1,000) for the best oral presentation among the six student finalists that were nominated in advance of the regular abstract deadline by the respective advisors, as selected by the GEC Student-Award Committee. Student award finalists will present their work on Tuesday, Wednesday, or Thursday, November 7-9. Here, student finalists are listed in the order of scheduled appearance in the GEC 2017 program.

Amanda Loveless, Purdue University
10:15 AM–10:30 AM, Tuesday, November 7, 2017
ROOM LOCATION: Duquesne Room
Session ET2: Modeling and Simulation I
Abstract: ET2.00002: ***Gas Breakdown: Across Length Scales and Frequency***

Sebastian Wilczek, Ruhr-University Bochum, Germany
11:15 AM–11:30 AM, Tuesday, November 7, 2017
ROOM LOCATION: Duquesne Room
Session ET2: Modeling and Simulation I
Abstract: ET2.00005: ***Differences between Cartesian and spherical 1d3v Particle-In-Cell simulations***

Derek Thompson, West Virginia University
1:45 PM–2:00 PM, Tuesday, November 7, 2017
ROOM LOCATION: Duquesne Room
Session FT2: Plasma Boundaries and Sheaths
Abstract: FT2.00002: ***3D ion and neutral distribution measurements and simulations of the boundary region of a magnetized plasma***

Vivien Croes, Ecole Polytechnique
2:00 PM–2:15 PM, Wednesday, November 8, 2017
ROOM LOCATION: Oakmont Junior Ballroom
Session MW3: Modelling of Propulsion and ExB Plasmas
Abstract: MW3.00003: ***Entangled effects of electron drift instability and secondary electron emissions in Hall effect thrusters: Insights from 2D PIC computations***

Basu Lamichhane, Missouri University of Science and Technology
2:30 PM–2:45 PM, Tuesday, November 7, 2017
ROOM LOCATION: Oakmont Junior Ballroom
Session FT3: Heavy Particle Collisions
Abstract: FT3.00003: ***Fully Differential Study of Capture with Vibrational Dissociation in p + H2 Collisions***

Amanda Lietz, University of Michigan
10:45 AM–11:00 AM, Thursday, November 9, 2017
ROOM LOCATION: Duquesne Room
Session RR2: High Pressure Discharges
Abstract: RR2.00004: ***Atmospheric Pressure Plasma Multi-jets: Fundamental Properties***

At the 69th GEC in Bochum, Germany, the award was presented to Adam Obrusnik, Masaryk University, for the oral presentation "Gas flow phenomena in atmospheric pressure plasma jets impinging on solid and liquid substrates investigated using numerical modelling and Schlieren imaging".

WEAR YOUR BADGE! – REGISTRATION DESK

The registration desk will be open on Monday, November 6 from 4:00 to 7:00pm in the Oakmont Junior Ballroom. Tuesday through Thursday the registration desk will be open from 8:00am to 3:00pm, located in the Hotel Lobby of the DoubleTree. Friday the registration desk will not be officially open. The on-site registration fees are:

Regular Attendee	$700
Retired/Unemployed	$400
Student	$400
One-Day Attendee	$375

LET'S CELEBRATE! – WELCOME RECEPTION, BANQUET RECEPTION, CONFERENCE DINNER

A welcome reception will be held 6:00-8:00pm on Monday, November 6 in the Oakmont Junior Ballroom. On Thursday, November 9 the banquet reception will be held at 6:30pm in Salons ABC, followed by the banquet at 7:30pm also in Salons ABC. The cost of the banquet is included in the registration fee. An Accompanying Person ticket is $225 if purchased by October 27, or on-site for $275. This ticket includes the Welcome Reception, 3 lunches (Tuesday/Wednesday/Thursday), the banquet reception, and conference dinner, but no coffee breaks. Attendees of the scientific sessions and coffee breaks are required to be a conference registrant. A single guest welcome reception ticket can be purchased for $60 and a single guest banquet ticket (reception and dinner) can be purchased for $100. These additional tickets must be purchased at the GEC registration desk on-site through Tuesday, November 7. All conference registrants and guests are encouraged to attend the banquet which will include recognition of the GEC Student Excellence Award and Poster Awards and will feature live background-music entertainment.

WHAT'S THAT? – WEST VIRGINIA UNIVERSITY LAB TOUR

A tour of some facilities of the WVU Plasma Physics Laboratory is offered on Saturday, November 11, according to the indication of interest, as can be accommodated. Register for the lab tour at the GEC Registration Desk. The lab tour takes place in Morgantown, WV, one hour driving distance from the DoubleTree Hotel, so scheduling transportation is important. The intention is to arrange a roundtrip shuttle bus for Saturday morning, November 11, returning to the DoubleTree and/or the airport in early afternoon.

STAY CONNECTED – WI-FI AND OTHER BUSINESS SERVICES

WiFi access is available in the public areas for GEC attendees with a separate access code. For a fee, services such as faxing, printing and photocopying are available in the Business Center area located near the Hotel Lobby.

THE SHOW MUST GO ON – AUDIO-VISUAL EQUIPMENT

The technical sessions will be equipped with an LCD projector, screen, and amplified sound. Laptops will be provided for the oral sessions, although speakers are advised to bring their own laptops for their talks. A speaker ready-room will be available for testing presentation-software compatibility.

MEALS ARE OPPORTUNITIES FOR NETWORKING – DINING OPTIONS

For descriptions and menus of the 3 dining options in the DoubleTree, please see http://doubletree3.hilton.com/en/hotels/pennsylvania/doubletree-by-hilton-hotel-pittsburgh-green-tree-PITGTDT/dining/index.html

Breakfast is on your own. The following DoubleTree venues are open for breakfast:

Asado Urban Grill: Fill up on delicious offerings at DoubleTree-Green Tree's flagship dining establishment, Asado Urban Grill. Guests enjoy sitting down for a home-style breakfast buffet each morning to refuel for another exciting day exploring Pittsburgh.

Bistro & Marketplace: Enjoy a refreshing fruit smoothie at the Bistro & Marketplace which offers the open, airy ambiance of your favorite corner café combined with modern touches and flexible seating. The inviting space and high connectivity make it the perfect place to enjoy a cup of Starbucks coffee and delicious snack while you surf the Internet.

Lunches will be served Tuesday through Thursday in Oakmont Junior Ballroom. The lunches are included in the GEC registration fees. Tuesday and Thursday lunches will be plated meals whereas Wednesday will be a delicatessen buffet.

Dinner is on your own. Take the free evening buses to downtown, or visit DoubleTree's

Champions Club at Asado Urban: Enticing any avid sports fan, Champions Club at Asado sports bar offers an enhanced media wall covered in paneled large flat-screen TVs and provides casual upscale food, ranging from refreshing salads to mouthwatering, juicy burgers to melt-in-your-mouth filet mignon.

SEE THE CITY LIGHTS – TRANSPORTATION TO DOWNTOWN

Two complimentary 54-passenger buses will loop from the DoubleTree to downtown Pittsburgh for 5 hours each evening starting Monday early evening and ending Thursday late evening from 6:30-11:30pm, to various downtown locations. The buses will be available in front of the DoubleTree. A different district will be featured each night. Station Square and the Southside district will be Tuesday's and Thursday's destination while the North Shore and the Northside district will be Wednesday's destination. Once at either destination, the subway allows convenient travel throughout the city.

NOW WE ROTATE THE GEC GENERAL AND EXECUTIVE COMMITTEES – CALL FOR NOMINATIONS

The GEC ExCom welcomes nominations, including self-nominations, for both the GEC General Committee and the GEC Executive Committee. Becoming a GenCom or ExCom member provides a unique opportunity to participate in GEC governance and see how one may influence GEC's future direction by helping to define scientific programs and select future venues. General Committee and Executive Committee members select special event topics, invited speakers, abstract-sorting categories. They arrange the technical program, select meeting sites, and vote on budgetary options. Please review the GEC Constitution and Bylaws for details, found on the GEC 2017 website.

New members of the GEC General Committee will be selected during the GEC2017 Business Meeting (the nominees must be attending the Business Meeting). The GenCom meets once, immediately after the Business Meeting. The ExCom meets twice per year: during the annual GEC meeting and at the Abstract-Sorting Meeting during June. Business is also conducted via email.

The 2017 Business Meeting will take place on Wednesday, November 8, at 11:00am in Salons DE. Written proposals to host future GEC meetings are encouraged and should be discussed with the Chair of the Executive Committee. The General Committee reviews all proposals and makes the final site selection. The selected host is then elected to a 3-year term on the Executive Committee as Secretary-Elect, becoming Secretary in year 2, and Past Secretary in year 3.

PLANT THE SEEDS FOR GEC2018 – CALL FOR INVITED SPEAKER RECOMMENDATIONS FOR THE 71ST GEC

The ExCom solicits recommendations for GEC2018 invited speakers from GEC2017 participants before 23:59 EST, Tuesday, 7 November. The ExCom will make the final selection of invited speakers for the 71st GEC, as specified in the GEC Constitution and Bylaws.

An invitation to submit a recommendation via the online submission website will be emailed. Please only use the web portal for submitting recommendations. Using the web portal is the only method to submit a recommendation.

PUBLISH AND PROMOTE THE FIELD – *PLASMA SOURCES SCIENCE & TECHNOLOGY* AND *JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS*

GEC invited-speakers in the Collisions category are invited to submit their conference article to the IOP journal *Journal of Physics B*, whereas GEC invited-speakers in all other categories are invited to submit their conference article to the IOP journal *Plasma Sources Science and Technology*. Articles are required to contain at least 30% of new and unpublished research and need to be within the scope of *JPhysB* and *PSST*, respectively. The articles will be reviewed to the usual *JPhysB* and *PSST* standards and published as regular papers. Once all the articles are published, they will be gathered on a web page dedicated to the 70th GEC and be free to download for a limited period. Further information can be requested from IOP Publishing or the Guest Editors.

Please contact the Guest Editors to submit your GEC invited-talk article.

For *PSST*:
Costel Biloiu (Applied Materials, Inc.)
<costel.biloiu@ieee.org>

Anne Bourdon (LPP Ecole Polytechnique) <anne.bourdon@lpp.polytechnique.fr>
Jean-Paul Booth (LPP Ecole Polytechnique) <jean-paul.booth@lpp.polytechnique.fr>

For *JPhysB*:
Tom Kirchner (York University) <tomk@yorku.ca>
Lorenzo Ugo Ancarani (Université de Lorraine), ugo.ancarani@univ-lorraine.fr>

RANK HAS ITS RESPONSIBILITIES – GEC 2017 EXECUTIVE COMMITTEE

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YOU HAVE QUESTIONS; WE HAVE ANSWERS – MEMBERS OF GEC 2017 LOCAL ORGANIZING COMMITTEE

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THANK YOU FOR YOUR SUPPORT! – GEC 2017 SPONSORSHIP

Sponsors and Exhibitors allow the GEC Executive Committee to provide many benefits to attendees including student-travel assistance and a student-excellence award. The 70th GEC has been fortunate to receive support from the following organizations (up to the time of this publication.) GEC is very grateful for the continued support from government and industry.

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Thanks to the generous support of sponsors, we have been able to accommodate the on-time student requests for travel assistance!

PLEASE VISIT OUR DISPLAY – GEC 2017 EXHIBITORS

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Extrel CMS
Lam Research Corporation
Hiden Analytical
West Virginia University
IOP Publishing
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Epitome of the 70th Annual Gaseous Electronics Conference

09:00 MONDAY MORNING
06 NOVEMBER 2017

AM1 **Linking Academia & Industry**
Room: Salon D

AM4 **Scientific Paper Writing Workshop**
Room: Foster

14:00 MONDAY AFTERNOON
06 NOVEMBER 2017

BM1 **Practical Challenges for Industry**
Room: Salon D

BM2 **Linking Theory & Experiment**
Room: Dusquene

18:00 MONDAY EVENING
06 NOVEMBER 2017

CM1 **Welcome Reception**
Room: Oakmont Junior Ballroom

08:00 TUESDAY MORNING
07 NOVEMBER 2017

DT1 **Microdischarges I**
Remi Dussart
Room: Salon D

DT2 **Diagnostics I**
Room: Duquesne

DT3 **Bio-Medical Plasma Chemistry**
Satoshi Uchida
Room: Oakmont Junior Ballroom

10:00 TUESDAY MORNING
07 NOVEMBER 2017

ET1 **Plasmas in Liquids I**
Paul Maguire
Room: Salon D

ET2 **Modeling and Simulation I**
Victor Pasko
Room: Duquesne

ET3 **Plasma Etching for Semiconductor Processing**
Keizo Kinoshita, Mingmei Wang
Room: Oakmont Junior Ballroom

13:30 TUESDAY AFTERNOON
07 NOVEMBER 2017

FT1 **Inductively Coupled Plasmas**
Room: Salon D

FT2 **Plasma Boundaries and Sheaths**
Michael Campanell
Room: Duquesne

FT3 **Heavy Particle Collisions**
Xinwen Ma, Ladislau Nagy
Room: Oakmont Junior Ballroom

16:00 TUESDAY AFTERNOON
07 NOVEMBER 2017

GT1 **Poster Session I**
Room: Salon ABC

08:00 WEDNESDAY MORNING
08 NOVEMBER 2017

JW1 **Gas Phase Plasma Chemistry I**
Room: Salon D

JW2 **Diagnostics II**
Jim Franek
Room: Duquesne

JW3 **Antimatter and Other Processes**
Michael Charlton,
Stephen Buckman
Room: Oakmont Junior Ballroom

10:00 WEDNESDAY MORNING
08 NOVEMBER 2017

KW1 **The Will Allis Prize for the Study of Ionized Gases**
Klaus Bartschat
Room: Salon D

11:00 WEDNESDAY MORNING
08 NOVEMBER 2017

LW1 **Business Meeting**
Room: Salon D

13:30 WEDNESDAY AFTERNOON
08 NOVEMBER 2017

MW1 **Microdischarges II**
David Go
Room: Salon D

MW2 **Non-equilibrium Kinetics of Low-temperature Plasmas**
Svetlana Starikovskaia
Room: Duquesne

MW3 **Modelling of Propulsion and E×B Plasmas**
Francesco Taccogna
Room: Oakmont Junior Ballroom

16:00 WEDNESDAY AFTERNOON
08 NOVEMBER 2017

NW1 **Poster Session II**
Room: Salon ABC

19:00 WEDNESDAY EVENING
08 NOVEMBER 2017

PW2 **LXCat Discussion**
Room: Duquesne

08:00 THURSDAY MORNING
09 NOVEMBER 2017

QR1 **Magnetically Enhanced Plasmas I**
Room: Salon D

QR2 **Diagnostics III**
Igor Adamovich
Room: Duquesne

QR3 **Collisions with Atoms**
N.L.S. Martin, Marcelo Ambrosio
Room: Oakmont Junior Ballroom

10:00 THURSDAY MORNING
09 NOVEMBER 2017

RR1 **Plasmas at Special Conditions**
Room: Salon D

RR2 **High Pressure Discharges**
Room: Duquesne

RR3 **Electron-Molecule Collisions**
Dmitry Fursa, Xiangjun Chen
Room: Oakmont Junior Ballroom

13:30 THURSDAY AFTERNOON
09 NOVEMBER 2017

SR1 **Modeling and Simulation II**
Hae June Lee, Jannis Teunissen
Room: Salon D

SR2 **Plasmas in Liquids II**
John Foster
Room: Duquesne

SR3 **Capacitively Coupled Plasmas**
A.R. Gibson
Room: Oakmont Junior Ballroom

16:00 THURSDAY AFTERNOON 09 NOVEMBER 2017

TR1 **Magnetically Enhanced Plasma II**
Denis Eremin
Room: Salon D

TR2 **Dissociation, Recombination, and Attachment**
Ioan F. Schneider, Nicholas Shuman
Room: Duquesne

TR3 **Biomedical Plasmas**
Klaus-Dieter Weltmann, Eric Robert
Room: Oakmont Junior Ballroom

18:30 THURSDAY EVENING 09 NOVEMBER 2017

UR1 **Reception and Banquet**
Room: Salon ABC

08:00 FRIDAY MORNING 10 NOVEMBER 2017

VF1 **Nanoparticles**
Room: Salon D

VF2 **Gas Phase Plasma Chemistry II**
Room: Duquesne

VF3 **Surface Treatment and Deposition**
Room: Oakmont Junior Ballroom

10:00 FRIDAY MORNING 10 NOVEMBER 2017

WF1 **Reconfigurable and Interacting Plasmas**
Sergey Macheret
Room: Salon D

WF2 **Plasma-Surface Interactions**
Room: Duquesne

WF3 **Environmental and Energy Applications**
Katsuhisa Kitano
Room: Oakmont Junior Ballroom

SESSION AM1: LINKING ACADEMIA & INDUSTRY
Monday Morning, 6 November 2017
Room: Salon D at 9:00
Julian Schulze, West Virginia University/Bochum University, presiding

Contributed Papers

9:00

AM1 1 Characterization and diagnostics of RF plasmas under manufacturing conditions MICHAEL KLICK, *Plasmetrex GmbH* There are many problems in the industrial usage of plasma processes. For the semiconductor industry as one of the most important examples, there are the following main targets: chamber matching, minimizing the first wafer effect, optimizing chamber conditioning, fault detection and Fault classification, and pre-process impact. From the plasma science of view, the analysis of these effects leads often to problems as not well defined and basically unknown chamber wall state (varying heavily with product processed), chamber and gas heating affecting also the chamber wall state, plasma mode transitions (e.g., E-H-mode) and its detection. In the most of industrial environments, there is a permanent lack of information of the state of the plasma. What are potential solutions? (1) Simplified models where complex parts and unknown boundary conditions are replaced by parametrization through real-time and in-situ sensors. (2) Complementary real-time and in-situ plasma sensors. These ideas lead to some challenges which have to be discussed. Those are the requirement of characterization of the plasma close to the substrate and for manufacturing sites to have a basic knowledge of plasmas and minimum understanding or their own plasma processes.

9:30

AM1 2 Progress on Voltage Waveform Tailoring for plasmas: From science to process, from lab to fab ERIK JOHNSON, *LPICM-CNRS, Ecole Polytechnique, University Paris-Saclay* SEBASTIEN DINE, *SOLAYL SAS* JEAN-PAUL BOOTH, *LPP-CNRS, Ecole Polytechnique, University Paris-Saclay* The use of Tailored Voltage Waveforms for the excitation of asymmetric plasmas is a useful tool both for process control and to understand the physics behind surface treatments. It has unveiled knowledge about processes such as deposition, etch, surface passivation, cleaning, doping, and texturing. However, despite recent interest, any hope of a large-scale application of this technique by a risk-averse plasma-processing industry means a clear path to simple implementation must become obvious. The engineering challenges to using this technique come from its multi-frequency nature; one must couple multiple harmonics of an RF frequency efficiently, and precisely know their phase and amplitude when they interact with the plasma. Our group has focused on addressing the practical issues that risk slowing the adoption of this technique, namely (1) efficient and affordable power coupling, and (2) a straightforward technique for calibration. For power coupling, we have progressed on the concept of multi-frequency impedance matching, and I will discuss trade-offs in cost, complexity, and control. Concerning calibration (i.e. knowing the waveform that appears at the electrode), I will discuss our "minimally-intrusive" techniques to do so.

10:00

AM1 3 The status of etching processes in semiconductor fabrication, and upcoming challenges JIN-YOUNG BANG, SUNGIL CHO, *Samsung electronics* Recently, etch processes have become increasingly important in semiconductor fabrication. Recent devices require very small critical dimensions and high aspect ratio contact holes or trenches. In terms of equipment, it should be designed to have high process accuracy, productivity and reproducibility. Therefore, a lot of efforts are made to secure the process capability and equipment stability in accordance with the development speed of semiconductor technology. In this presentation, the problems that arise in the latest semiconductor manufacturing are introduced from the viewpoint of process, equipment, and manufacturing. We will also discuss the new technologies requires to realize sub-10 nm and aspect ratio of 100 or more required for next-generation devices.

10:30

AM1 4 Successes, Failures, and Lessons Learned Navigating Industry Supported Research in Academia STEVEN SHANNON, *North Carolina State University* Collaborations between academia and industry can be very productive for both sides. The technical contributions of the research, access to new graduates trained in critical areas, and future revenue that can be generated by these partnerships are extremely attractive to industry. The monetary support for research endeavors and direct collaboration with industry researchers to identify science challenges in industry strengthen academic research endeavors. The opportunity to work alongside industry is extremely attractive for students and young scholars, many of whom seek to move into the private sector after graduation. With that come challenges in formalizing partnerships between academia and industry. Ownership of technology, vetting of publications, disparity in timescale expectations, and short term research agreements are only a few examples of pitfalls that can make compelling partnerships perish. In this talk, examples of collaborations between industry and academia from both the industry and academic perspective will be presented, focusing on what went right, what went wrong, and the evolution of a successful framework for these collaborations through these experiences. Identification of roadblocks and strategies for navigating partnerships through to formal research agreements will be presented.

11:00

AM1 5 Application Perspective of Plasma Science and Technology for Food and Agriculture WONHO CHOE, *Korea Adv Inst of Sci & Tech* CHEORUN JO, *Seoul National University* YOUBONG LIM, *Plasmapp* SUK-JAE YOO, *NFRI* The plasma science and technology can bring about innovations in agriculture and food industries using the plasma's unique properties. As a part of the '*Plasma Farming*', a comprehensive application of the plasma to the entire agricultural stages from farm to table, the application of atmospheric pressure plasma (APP) on the food industry is promising. The APP can bring highly ensured safety and extended shelf-life, which would ultimately provide a comprehensive solution to challenges in the food industry. In this presentation, example-based discussions will be made particularly for the food safety, the food processing, and the novel smart plasma packaging. Food safety is undoubtedly of the highest priority for both food industry and consumers, and the APP can be a promising means. Several examples of antimicrobial effects of the plasma treatments will be discussed to show the plasma's role as an excellent non-thermal sterilization means. In addition, the developed APP packaging technology can inactivate pathogens in packaged food by using a flexible pouch type plasma source, in which reactive oxygen and nitrogen species are produced from the ambient air inside the pouch. Another creative application of the APP is plasma treated water, which can be used as an alternative nitrite source—the most important curing agent of processed meat—along with the direct use of the plasma in the processed meat manufacturing. The requirements and conditions for developing appropriate plasma sources will also be discussed.

11:30

AM1 6 The application of the multipole resonance probe to industrially relevant processes MORITZ OBERBERG, MARCEL FIEBRANDT, STEFAN RIES, CHRISTIAN WOELFEL, PETER AWAKOWICZ, *Ruhr-University Bochum* INSTITUTE OF ELECTRICAL ENGINEERING AND PLASMA TECHNOLOGY TEAM The Multipole Resonance Probe (MRP) has recently been introduced as a novel diagnostic for electron density measurements. Based on active plasma resonance spectroscopy (APRS), the probe measures a resonance whose frequency depends mainly on the electron density. Benchmark measurements in different low pressure plasmas are presented. A lot of academic work such as modeling, simulations, and experiments was done in recent years to develop the MRP. Here, measurements in industrial processes such as sputtering and plasma ion assisted deposition (PIAD) are presented. Due to the ceramic tube surrounding the probe, it is very insensitive against dielectric coatings as long as the coating's thickness is small compared to the thickness of the ceramic tube. Thus, the MRP is a highly functional and fast diagnostic for such deposition processes, where other diagnostics, e.g. Langmuir probes, fail. It can be used for real-time process monitoring and has been tested in control loops to stabilize deposition processes. Further challenges for both academia and industry are addressed such as the compensation of the rf modulated sheath as well as the search for actuation variables in control loops and the dependence of film properties on the control working point.

SESSION AM4: SCIENTIFIC PAPER WRITING WORKSHOP
Monday Morning, 6 November 2017
Room: Foster at 9:00
Mark Koepke, West Virginia University, presiding

Contributed Papers

9:00

AM4 1 Scientific Paper Writing Workshop BODIL HOLST, *Nanophysics Group, University of Bergen, Norway* The Scientific Paper Writing Workshop has two main goals. Firstly, to provide the participants with a set of "tools" helping them to present their scientific results in a clear and interesting way and, secondly, to make them aware of various strategic issues connected to paper writing (in which journal to publish, cover letter to the editor, etc.). The workshop is presented in English. The participants are encouraged to bring drafts of own papers, in particular an abstract for at least one paper, but this is not a prerequisite.

SESSION BM1: PRACTICAL CHALLENGES FOR INDUSTRY
Monday Afternoon, 6 November 2017
Room: Salon D at 14:00
Douglas Keil, LAM, presiding

Contributed Papers

14:00

BM1 1 Use of plasma sensors combined with artificial intelligence in the diagnostics and monitoring of plasma processes MICHAEL HOPKINS, CLIODHNA HARRISON, PAUL SCULLIN, DAVID GAHAN, *Impedans Ltd.* In processes using plasma the general practice is to use limited diagnostics to analyze the plasma in the development phase. Plasma measurement is not generally used to monitor the process during production when the plasma is manufacturing product. The main reason appears to be linked to the cost and complexity of the plasma measurement systems. With the growth of big data there is a renewed interest in applications where internet enabled sensors are deployed to monitor the performance of high cost capital equipment and improve productivity and reduce cost. In this paper we examine data measured from plasma processes and analyzed automatically. The measurement data is combined with context data which defines the state of the plasma processes, type of chamber, gas type, pressure, power and any other relevant parameter. The data is collected and stored in a data base. Software scripts can read the data base and display the data using complex visualization techniques. A model of each process is developed and stored. Subsequent out of sample data is then analyzed, stored and an automatic report generated describing the plasma state and any deviation from expected values. The report is designed to be read by an engineer, who is not necessarily a plasma expert and contains text and graphs. This is an attempt to create an expert system to implement plasma diagnostics as part of routine monitoring of plasma processes. We will outline in more detail the concept and techniques and report our initial outcomes and show examples of the reports generated.

14:30

BM1 2 The significance of RF power delivery for thin-film semiconductor plasma processes and the enhancements of innovative solutions DAVID J. COUMOU, *MKS Instruments, Inc.* Many critical technologies rely on plasma-based material processing. Plasma processing is one of the cornerstone technologies for the semiconductor industry for its significant role in material surface interactions, thereby broadly impacting other market sectors such as display technologies, energy efficient building supplies, flexible electronics, bio-compatible materials and devices, and low cost photovoltaics. From film growth to patterning structures in high-volume manufacturing environments, a key subsystem enabling this breadth of capability is the RF power delivery systems. In this talk, we explore advances in RF power delivery systems with corresponding enablement of plasma processes ameliorating many advanced manufacturing processes. We start with basic fundamental plasma physics and the interaction of RF coupling to plasma densities. These influences are then leveraged to improve uniformity and sheath voltage tailoring for ion energy control. We exploit this capability for both inductive and capacitively coupled plasma reactors used in semiconductor manufacturing. We include the advent of evolving technologies for the enhancement of distortion cancellation prevalent in multi-frequency reactors and RF power delivery factors to improve chamber matching.

15:00

BM1 3 Plasma etch reactor design challenges for high RF power applications ALEXEI MARAKHTANOV, *Lam Research Corporation* Plasma etching of dielectric structures of advanced semiconductor devices faces multiple challenges due to the requirements posed by scaling at advanced technology nodes. Increasing high aspect ratio of next generation memory devices requires substantial increase in ion energy and ion flux with nearly perfect plasma uniformity above the substrate. To meet these process requirements, design of small volume confined plasma reactor becomes a technical challenge. New aspects of the design, such as voltage and power management with increased applied RF powers will be discussed in this presentation.

15:30

BM1 4 Atomic Layer Processing of Silicon Dielectrics: Precursors, Processes, and Plasmas DAVID C. SMITH, *Lam Research Corporation* Atomic layer deposition (ALD) and atomic layer etching (ALE) are advanced methods for achieving the formation of nanometer-sized features. Plasma-assisted ALD is the best-known method to meet low temperature (<500 °C) requirements and is now being used for depositing conformal silicon dielectrics such as silicon oxide (SiO_2) and silicon nitride (Si_3N_4). Atomic layer etching (ALE) is an advanced etch technique used in the fabrication of 10 nm logic devices. By virtue of its separated and self-limiting steps, ALE offers a simplified system in which to understand etch mechanisms. The current state of the art of chemistries, plasmas, and process conditions required for the processing of silicon dielectrics by plasma ALD and ALE will be discussed.

16:00

BM1 5 Advanced HIPIMS solution for R&D and Process Development SEAN ARMSTRONG, *Kurt J. Lesker Company* When HIPIMS was first introduced to the thin film coating industry, it was considered an advanced technique for production applications, which would provide optimal film properties and wear resistance. The HIPIMS supply options were very large scale directly suited to the production industry. However, it was found to have significant limitations in rate, which minimized its acceptance in production applications. Recently, the introduction of smaller scale supplies triggered an emergence of the technology into the R&D community. This enabled a high rate of enhancements and helped innovate a more efficient capability and process optimization that could be utilized by HIPIMS supplies. This ultimately re-energized the interest and potential of HIPIMS in the thin film coating industry. One of the solutions to emerge from the crowd was the IMPULSE supply, which brings a unique range of features to the HIPIMS community. The IMPULSE is a 2kW supply that is offered in a single and dual configuration. It features touch panel controllability, the fastest pulse frequency, 200A peak current, and the most competitive pricing in the industry. The supply is slave capable and can be scaled from its 2kW standard configuration by adding additional units. This makes it an excellent option for process development. Test results will be shared that show its unique performance capabilities and compatibility with higher scale power requirements.

16:30

BM1 6 Practical challenges for the integration and application of plasmas in atomic layer deposition systems J. R. GAINES, *Kurt J. Lesker Company* Atomic Layer Deposition (ALD) is the fastest growing thin film deposition technology, for 2017 and for foreseeable future. Increased complexity impressed on the semiconductor industry in the transition to 3 dimensional transistor designs and the traditional pressures on device density make ALD a natural tool for current and future challenges. The design shift to 3D structures substantially complicates the development of robust ALD processes for certain materials. The chemical mechanisms at the heart of ALD in some cases require additional energy beyond what can be promoted through high temperature reactions. Certainly, for certain iconic materials such as platinum, plasmas much be integrated into the ALD system to achieve high quality results. In this presentation specific issues related to the integration and application of plasma technology to the chemical deposition of molecules on solid substrates will be reviewed.

SESSION BM2: LINKING THEORY & EXPERIMENT

Monday Afternoon, 6 November 2017
Room: Dusquene at 14:00
Thomas Mussenbrock, Brandenburg University of Technology, presiding

Contributed Papers

14:00

BM2 1 Modeling of industrial plasma tools and applications: experimental validation SHAHID RAUF, SAMANEH SADIGHI, AJIT BALAKRISHNA, KALLOL BERA, JASON KENNEY, WEI TIAN, JUN-CHIEH WANG, *Applied Materials, Inc.* Plasmas are widely used for thin film processing during microelectronics fabrication. Modeling is an important tool for design of these plasma systems, and experimental validation of these models is important. Rapid pace of technology development makes such validation challenging in an industrial environment. Several examples are used to illustrate different methods for validating and refining models of industrial plasma systems. Ideally, systematic plasma diagnostic measurements should be made on the actual plasma tool as was the case in our multi-frequency capacitive plasma source. n_e and T_e were measured using double probes in the 2–162 MHz range for several gases and pressures. If diagnostic data from the actual tool is not available, another option is to validate the models under similar conditions in a research reactor. For example, we are collaborating with Ecole Polytechnique on diagnostics in inductively coupled Cl_2, Cl_2/O_2 and HBr plasmas. Final processing results (e.g., etch rate) are often the most easily available data. Validating plasma models using such data relies on coupling the plasma simulations to a surface chemistry mechanism. Surface chemistry introduces uncertainties, but often the model can be reasonably validated if the data covers a wide range of conditions.

14:30

BM2 2 Validation of computation by Experiment for the VSim and USim Codes JOHN CARY, *Univ of Colorado - Boulder and Tech-X Corporation* SN AVERKIN, KRC BECKWITH, BM COWAN, TG JENKINS, SE KRUGER, M KUNDRAPU, C ROARK, SW SIDES, *Tech-X Corporation* GR WERNER, *Univ of Colorado - Boulder* The Tech-X codes, VSim and USim, have been used for modeling a wide range of plasma systems, including low-temperature plasma systems. VSim works on a structured cartesian or cylindrical mesh, has electrostatic and electromagnetic solvers, fluid models, and particle models. USim works on an unstructured hex mesh, has solvers for electromagnetics and fluids, and is particularly suited to studying high-Mach flows. VSim is more oriented towards low-density, weakly collisional systems, while USim is more oriented towards high-density, collisional systems. These codes have been tested on a number of standard problems in low temperature plasma, including the GEC Reference Cell and the Turner benchmarks, as well as being tested for solution accuracy for electromagnetics of structures. This talk will briefly describe the physics implementations in these codes, then show comparisons with experimental data.

15:00

BM2 3 Combining advanced optical diagnostics and simulations to reveal chemical kinetics in atmospheric pressure plasmas* SANDRA SCHROETER, J. BREDIN, A. R. GIBSON, A. WEST, A. WIJAIKHUM, K. NIEMI, H. DAVIES, N. MINESI, J. DEDRICK, *University of York* M. FOUCHER, J. P. BOOTH, *LPP, Ecole Polytechnique-CNRS* N. DE OLIVEIRA, D. JOYEUX,

L. NAHON, *Synchrotron SOLEIL* Y. GORBANEV, V. CHECHIK, E. WAGENAARS, T. GANS, D. O'CONNELL, *University of York* Atmospheric pressure plasmas (APPs) are effective sources of reactive species (RS) and offer great potential for various applications, such as in biomedicine. Experimental quantification of RS is challenging in APPs due to their small dimensions and fast collisional de-excitation of excited states, requiring diagnostics with high temporal and spatial resolution. Plasma simulations give information about species densities and formation, but their accuracy depends on assumed reactions and rate coefficients, meaning that a benchmark against experimental measurements is desirable. Here, experimental and numerical approaches are combined to investigate RS production in rf APPs produced in a helium-water gas mixture. Absolute densities of O, H, OH, and H_2O_2 are measured using advanced optical diagnostics including VUV-VIS Absorption Spectroscopy in the liquid and gas phase, and picosecond Two-photon Absorption Laser-Induced Fluorescence, which are able to overcome the above-mentioned challenges. The successful benchmark of densities against a zero-dimensional plasma chemistry model allows for detailed investigation of formation pathways and identification of tailoring strategies based on varying gas composition and reactor design.

*Supported by UK EPSRC (EP/K018388/1, EP/H003797/1), the York-Paris CIRC and LABEX Plas@par (ANR11-IDEX-0004-02).

15:30

BM2 4 Linking experimental measurements and numerical simulations to understand plasma-surface interaction processes* A. R. GIBSON, M. BLAKE, J. BREDIN, K. NIEMI, A. GREB, *University of York, UK* B. BRUNEAU, E. JOHNSON, *LPICM-CNRS, France* A. DERZSI, Z. DONKO, *Wigner Research Centre, Hungary* J.-P. BOOTH, *LPP-CNRS, France* D. O'CONNELL, T. GANS, *University of York, UK* Surfaces play a key role in defining the properties of low-pressure plasma sources through the destruction of reactive neutral species. However, despite their importance, fundamental data concerning particle-surface interactions in plasmas are often poorly known as a result of difficulties in experimentally measuring surface interaction probabilities in active plasmas. Combining experiments and numerical simulations offers a promising route overcome the associated challenges and better understand surface interaction processes. In this work, phase resolved optical emission spectroscopy (PROES) and energy resolved acinometry (ERA) are used in combination with numerical simulations (one-dimensional PIC and fluid) to gain insight into surface losses of singlet delta oxygen metastables and atomic oxygen in low pressure radio-frequency driven capacitively coupled oxygen plasmas.

*Funding through LABEX Plas@Par ANR-11-IDEX-0004-02 and UK EPSRC (EP/K018388/1) is acknowledged.

16:00

BM2 5 The effects of elementary surface processes on the plasma parameters in capacitively coupled radiofrequency discharges* ARANKA DERZSI, *West Virginia University* BENEDEK HORVATH, *Wigner RCP* MANASWI DAKSHA, *West Virginia University* BIRK BERGER, SEBASTIAN WILCZEK, JAN TRIESCHMANN, *Ruhr-University Bochum* THOMAS MUSSENBROCK, *Brandenburg University of Technology, Germany* PETER AWAKOWICZ, *Ruhr-University Bochum* ZOLTAN DONKO, *Wigner RCP* JULIAN SCHULZE, *West Virginia University* The elementary processes taking place at the boundary surfaces in capacitively coupled plasmas (CCPs) can largely influence the electron power absorption dynamics. Here, the effects of plasma particle-surface processes on the discharge characteristics are investigated by PIC/MCC simulations. Realistic description of the secondary electron emission (SEE) induced by heavy particles and electrons is implemented in the PIC/MCC model. Simulations are performed for a wide range of operating conditions in Argon by switching on/off the different elementary surface processes. In this way the effects of the individual processes on the plasma properties are separated. The results show that the secondary electron yield strongly depends on the discharge conditions and surface properties. At low pressures, the electron induced SEE is found to have an important role in the ionization dynamics. Therefore, we propose this process to be included in PIC/MCC simulations of CCPs in order to obtain more realistic results.

*Work supported by the US NSF Grant 1601080, by the German DFG SFB TR 87, and Hungarian K-119357 and PD-121033 Grants.

16:30

BM2 6 Sputtering process data interpreted by heavy particle simulations* JAN TRIESCHMANN, STEFAN RIES, NIKITA BIBINOV, PETER AWAKOWICZ, *Ruhr University Bochum, Germany* STANISLAV MRAZ, JOCHEN M. SCHNEIDER, *RWTH Aachen University, Germany* THOMAS MUSSENBROCK, *Brandenburg University of Technology Cottbus - Senftenberg, Germany* The initial step toward a reliable prediction of plasma sputter deposition is a benchmark comparison of numerical models with experimental data. In addition to only a reconstruction, however, imperative insight can be gained from the internal state of the applied model. This reasoning is exemplified with an investigation of two sputtering discharges both operated at gas pressures below 1 Pa. Firstly, a large scale multi-frequency capacitively coupled plasma (MFCCP) is considered as characterized experimentally by spatially resolved plasma and deposition diagnostics. Using a kinetic simulation approach, the previously unexplained non-equilibrium transport kinetics is unraveled from calculated spatially resolved sputtered particle distribution functions. Secondly, for a direct current magnetron sputtering (dcMS) discharge experimentally determined sputtered particle density maps and deposition profiles are complemented with numerical simulation results. For different target materials and gas admixtures, the model reconstructs experimental density profiles and, moreover, predicts the inherent deposition efficiency.

*Financial supported by the Deutsche Forschungsgemeinschaft (DFG) in the frame of transregional collaborative research centre TRR 87.

SESSION CM1: WELCOME RECEPTION
Monday Evening, 6 November 2017
Room: Oakmont Junior Ballroom at 18:00

18:00

CM1 1 Welcome Reception

SESSION DT1: MICRODISCHARGES I
Tuesday Morning, 7 November 2017; Room: Salon D at 8:00; Katsuhisa Kitano, Osaka University, presiding

Invited Papers

8:00
DT1 1 Microdischarge integration on silicon based devices*
REMI DUSSART, *GREMI - University of Orleans - CNRS*

DC Microhollow cathode discharges (MHCD) were first introduced in the mid 90's [1]. Due to their dimensions and their large surface to volume ratio, the produced microplasmas remain cold and can stably operate at atmospheric pressure in the normal regime provided the cathode area is not fully utilized [2]. Silicon processing intensively developed for microelectronic devices offers many opportunities to design new, original and efficient devices to produce high density microplasmas [3]. Our microreactors are made using processes including steps of oxidation, lithography, magnetron deposition and etching. In our device configuration, the dielectric separating the two electrodes is made of thermal SiO_2 and is 6 um thick so that a very high electric field is obtained before breakdown. However, in our device configuration, no field effect assisted breakdown was evidenced. With a cathode of silicon, the operation of our microdischarge arrays is very unstable and produces many current spikes that significantly damage the microcavities and lead to device failure. The mechanism responsible for this unstable operation and short lifetime was observed by other groups [4] and were investigated [5]. The different possibilities to enhance the stability of microdischarges made from silicon wafers will be discussed. One of them consists in using a thin metal film on the silicon cathode. The devices were then tested in 3 different gases (He, Ar N_2) and in the air. We will show that a very stable operation can be obtained using this new configuration. The lifetime of the microreactors with a confined cathode is significantly enhanced.

*The authors gratefully acknowledge the support by the DAAD and the Campus France in the frame of a PROCOPE cooperation (Project Number 33340PC).

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[2]T. Dufour *et al.*, Appl. Phys. Lett. **93**, 71508 (2008).
[3]J. G. Eden *et al.*, J. Phys. D: Appl. Phys. **36**, 2869 (2003).
[4]C. Sillerud *et al.*, Phys. Plasmas **24**, 033502 (2017).
[5]V. Felix *et al.*, PSST **25**, 025021 (2016).

Contributed Papers

8:30
DT1 2 Detection of CN (B $^2\Sigma^+$) in cold atmospheric plasma jet in argon JAYR AMORIM, MARCO RIDENTI, *Departamento de Fisica, Instituto Tecnologico de Aeronautica* CN($B^2\Sigma^+ \rightarrow X^2\Sigma^+$) violet system was investigated using optical emission spectroscopy in a non-equilibrium microwave atmospheric-pressure plasma jet in argon expanding in air. From the analysis of the emission spectra of the discharge in the range of 380 nm and 400 nm, the violet system of CN was found to be overlapped with the N_2^+ ($B^2\Sigma_u^+$, v=1$\rightarrow X^2\Sigma_g^+$, v=1) and N_2($C^3\Pi_u \rightarrow B^3\Pi_g$) bands, sequence Δv=-3. Data fitting procedure was numerically implemented by means of a homemade routine to disentangle the overlapped spectra of the three different band systems. Through this deconvolution technique it was possible to determine the CN ($B^2\Sigma^+ \rightarrow X^2\Sigma^+$) band head intensity as function of discharge powers between 30 W and 150 W and fluxes between 2.5 slm and 10.0 slm. Maximum intensity of violet band head was found for power of 150 W, flux of 2.5 slm, and for 10.0 slm power of 100W, showing that both power and flow rate increase the cyan violet system emission. Small admixture of nitrogen to the flux put in evidence the importance of excited nitrogen states in the formation of the CN (B $^2\Sigma^+$) state. The rotational temperatures and vibrational temperature were determined for the upper state level CN (B $^2\Sigma^+$).

8:45
DT1 3 Generation of energetic electrons in a plasma source at fore-vacuum pressures* YEVGENY RAITSES, SOPHIA GERSHMAN, *Princeton Plasma Phys Lab* A DC plasma source with a cylindrical anode and planar cathode separated with a mm-scale distance was operated in a vacuum chamber filled with argon and nitrogen gases at 1-10 torr, without the gas flow. Plasma was characterized with electrostatic probes and optical emission spectroscopy. Results of measurements demonstrate that the operation of this source is governed by non-local electron kinetics. Electrons produced by ion-induced secondary electron emission are accelerated in the cathode sheath and generate the plasma inside and other the plasma source. Calculations showed that at the above operating pressure, the energy relaxation length is larger than the distance between the electrodes. We will also report on controlling of electron energy distribution function in the generated plasma outside the source.

*This work was supported by the U.S. Department of Energy (DOE), Office of Science, Fusion Energy Sciences (FES) under DOE Contract No. DE-AC02-09CH11466.

9:00
DT1 4 High power electromagnetic filtering with plasma generation in rectangular Fabry-Perot type cut-resonators KONSTANTINOS KOURTZANIDIS, LAXMINARAYAN RAJA, *The University of Texas at Austin* Microwave breakdown between all-dielectric resonators has been recently proposed as an efficient way of generating small scale plasmas. At resonant frequencies, electromagnetic fields radiate in the gap between two resonators leading to local field enhancement and plasma formation. We study numerically with a high fidelity electromagnetic-plasma solver, the possibility of efficient high power filtering using arrays of all-dielectric cut-resonators. We characterize the transient plasma formation as well as its steady state under various configurations and input parameters. We demonstrate that using rectangular all-dielectric Fabry-Perot type cut-resonators, full transmittance at resonant frequencies

TUESDAY MORNING \ DT1

is being canceled when the incident wave power leads to local breakdown. The plasma discharge is formed at the antinodes locations of the standing wave pattern radiating between the arrays of resonators and its spatial extend, maximum electron density and localization depends on the gap size, the operating frequency, the input power as well as the background gas pressure. The application of this power filtering concept to a waveguide structure is also studied, showing that the proposed idea can be used in realistic transmission line configurations.

SESSION DT2: DIAGNOSTICS I

Tuesday Morning, 7 November 2017
Room: Duquesne at 8:00
Vince Donnelly, University of Houston, presiding

Contributed Papers

8:00

DT2 1 Electron neutral collision frequency measurements with the hairpin resonator probe* DAVID PETERSON, *North Carolina State University* PHILIP KRAUS, THAI CHENG CHUA, *Applied Materials Inc.* STEVEN SHANNON, *North Carolina State University* Electron neutral collision frequency is measured over pressures ranging from 0.1-2.0 Torr in Ar, He, Ar-He, and N_2 plasmas. Measurements are made with both grounded and fully floating hairpin resonator probes in a symmetric parallel plate capacitively coupled system driven at 27 MHz. The analysis treats the hairpin probe as open circuit two wire transmission line immersed in a dielectric medium. Results are compared to hybrid plasma equipment module (HPEM) simulations, showing good agreement with simulated collision frequency. Appropriate sheath models are shown to be a factor in determining measured quantities. Additionally, models that either include or neglect the RF sheath are compared for grounded and floating probes, respectively. The possibility of inferring both mean electron energy and dissociation fractions in N_2 from measured collision frequency is also briefly discussed.

*Work supported by a generous gift from Applied Materials Inc.

8:15

DT2 2 A Kinetic Approach to the study of Ideal Multipole Resonance Probe JUNBO GONG, ŠEBASTIAN WILCZEK, *Institute of Theoretical Electrical Engineering, Ruhr-University Bochum, Germany* JENS OBERRATH, *Institute of Product and Process Innovation, Leuphana University Lüneburg, Germany* DENIS EREMIN, *Institute of Theoretical Electrical Engineering, Ruhr-University Bochum, Germany* MICHAEL FRIEDRICHS, *Institute of Product and Process Innovation, Leuphana University Lüneburg, Germany* RALF PETER BRINKMANN, *Institute of Theoretical Electrical Engineering, Ruhr-University Bochum, Germany* Active Plasma Resonance Spectroscopy (APRS) denotes a class of industry-compatible plasma diagnostic methods which utilize the natural ability of plasmas to resonate on or near the electron plasma frequency. One particular realization of APRS with a high degree of geometric and electric symmetry is Multipole Resonance Probe (MRP). The Ideal MRP (IMRP) is an even more symmetric idealization which is suited for theoretical investigations. In this work, a spectral kinetic scheme is presented to investigate the behavior of the IMRP in the low pressure regime. The scheme consists of two modules, the particles pusher and the field solver. The particle pusher integrates the equations of motion for the studied particles. The Poisson solver determines the electric field at each particle position. The fluid model is studied to provide the initial conditions of simulation for optimization reason. The proposed method overcomes the limitation of the cold plasma model and covers kinetic effects like collisionless damping.

8:30

DT2 3 Planar Multipole Resonance Probe: A kinetic model based on a functional analytic description* MICHAEL FRIEDRICHS, *Institute of Product and Process Innovation, Leuphana University Lüneburg* RALF PETER BRINKMANN, *Institute of Theoretical Electrical Engineering, Ruhr-University Bochum* JENS OBERRATH, *Institute of Product and Process Innovation, Leuphana University Lüneburg* Measuring plasma parameters, e.g. electron density and electron temperature, is an important procedure to verify the stability and behavior of a plasma process. For this purpose the multipole resonance probe (MRP) represents a satisfying solution. However, the influence of the probe on the plasma due to its physical presence makes it unattractive for processes in industrial applications. As an improvement the planar design of the MRP (pMRP) was introduced, which combines the advantages of the spherical MRP with the possibility to be integrated into the chamber wall of a plasma reactor. To measure the electron temperature with the pMRP, a kinetic model of the probe-plasma system is necessary. In this work such a kinetic model based on a functional analytic description will be presented.

*The authors gratefully acknowledge funding by the German Research Foundation (DFG) within the project OB 469/1-1, BR 2190/6-1 and the BMBF project PluTO+.

8:45

DT2 4 Block Gauss-Seidel algorithm to analyze collisionless damping in the spectrum of the spherical impedance probe* JENS OBERRATH, *PPI, Leuphana University Lueneburg* "Active plasma resonance spectroscopy" (APRS) is a diagnostic method to measure plasma parameter like electron density and temperature. Measurements with APRS probes in plasmas of a few Pa typically show a broadening of the resonance peak due to kinetic effects. To analyze the broadening a general kinetic model in electrostatic approximation based on functional analytic methods has been presented [1]. One of the main results is, that the system response function Y is given in terms of the matrix elements of the resolvent of the dynamic operator evaluated for values on the imaginary axis. To determine the response function of the spherical impedance probe the resolvent has to be approximated by the inverse of a huge matrix, which is given by a banded block structure. To ensure a converged approximation of Y, the size of this matrix has to increase, if the collision frequency decreases. Thus, a numerical scheme with a minimum of memory demand and numerical errors is needed, especially in the limit of vanishing collisions. A promising choice is given by a block Gauss-Seidel algorithm, which utilizes the sparse banded block structure of the matrix.

*The authors gratefully acknowledge funding by the German Research Foundation (DFG) within the project OB 469/1-1.

[1] J. Oberrath and R. P. Brinkmann, Plasma Sources Sci. Technol. **23**, 045006 (2014).

9:00

DT2 5 Measurement of Langmuir probe sheath using dusty plasma T. E. SHERIDAN, *Ohio Northern University* The radius of the sheath around a thin cylindrical Langmuir probe is measured using dust. The probe tip is oriented perpendicularly to the horizontal, powered electrode in an rf discharge. The current-voltage characteristic of the probe is measured without dust and then with dust. The negatively-charged dust particles are repelled from the probe tip when the probe bias is below the plasma potential, creating a dust-free circular region around the probe tip. We observe a slight decrease in plasma density with dust which is consistent with electron depletion. The probe sheath radius, which we assume is the radius of the dust free region, decreases roughly like the square root of the probe bias. Plasma parameters measured using the Langmuir probe will be compared with measurements using two free-floating dust particles.

9:15

DT2 6 Plasma Density Perturbation by Microwave and Magnetic Probes VALERY GODYAK, *Retired* NATALIA STERNBERG, *Clark Un.* Magnetic probes (B-dot, or BDP) have been used over decades for measurement of rf electric field and plasma current. Recently, a variety of microwave probes (MWPs) has been proposed for plasma density measurement. In both cases, insertion of B-dot or microwave probes causes unaccounted plasma disturbance around the probe. Recent analyses of MWP probes has shown that they are based on too simplified and unrealistic assumptions about plasma uniformity, sheath capacitance evaluation, cold plasma permittivity, and a Maxwellian EEDF. The assumption of plasma uniformity around the probe is the most serious and common drawback of all MWP and the majority of BDP techniques. Plasma perturbation by a probe has the same localization area as that of MWP and BDP sampling area. This may result in essential difference between measured plasma parameters and those in absence the probe. In this presentation, we give an analysis of plasma perturbations by a spherical probe for arbitrary collisionality. The results were obtained by solving numerically a set of fluid equations for neutral plasma with cold ions, taking into account ion inertia and nonlinear ion friction force. In addition, an analytical solution was found for the collisionless case. The calculation showed a significant plasma density depletion around the probe growing with gas pressure. The depletion of plasma density should underestimate plasma density values inferred from MWP measurement, and dramatically distort rf field and current within BDP. The last is demonstrated for rf field and current distributions in inductive discharge at low gas pressure.

SESSION DT3: BIO-MEDICAL PLASMA CHEMISTRY

Tuesday Morning, 7 November 2017; Room: Oakmont Junior Ballroom at 8:00; Danil Dobrynin, Drexel University, presiding

Invited Papers

8:00

DT3 1 Numerical Investigation of Interactions between Reactive Oxygen Species and Biological Membrane in Atmospheric Nonequilibrium Plasma with Molecular Dynamics

SATOSHI UCHIDA, *Tokyo Metropolitan University*

Recently, direct contact processes of plasma species with various substances such as liquids and biomaterials have been established using stable nonequilibrium plasma under atmospheric pressure. The advanced plasma technology has been applied to industrial treatments. In particular, plasma medicine is one of the most attractive applications. However, various interactions among multiphase interfaces are extremely complicated. Theoretical modeling and numerical simulation are essential for understanding of the above mechanism. For multiphase behaviors among plasma, gas, liquid and biological objects, the numerical simulations using molecular dynamics are suitable because of the simplicity on physical mechanics. In the present work, fundamental modeling of multiphase including plasma, gas, liquid and biological objects under atmospheric pressure is introduced, and typical procedures of molecular dynamics are briefly described. Some analytical examples of plasma - biological interface are reviewed in the latest topical applications. The chemical reactions between reactive oxygen species and biomolecule are described with respect to the temporal energy balance. The transport characteristics of reactive oxygen species in biological membrane are also discussed.

Contributed Papers

8:30

DT3 2 Effects of gas-phase reactive species on generation of hydrogen peroxide and nitrite ion in plasma-activated medium KEIGO TAKEDA, *Meijo Univ.* NAOYUKI KURAKE, KENJI ISHIKAWA, HIROMASA TANAKA, MAKOTO SEKINE, MASARU HORI, *Nagoya Univ.* Plasma-activated medium (PAM) which is cell-culture medium irradiated by atmospheric pressure plasma jet (APPJ) has strong antitumor effects on the various kinds of cells. The irradiation of APPJ to the medium generates reactive oxygen and nitrogen species (RONS) in the aqueous-phase. The contributions of RONS in the PAM have been investigated to clarify the mechanism of selective killing of cancer. Hydrogen peroxide is well-known as one of reactive oxygen species to affect the cell response. Moreover, the synergic reactions of hydrogen peroxide and nitrite ion achieves the antitumor effect [1]. In order to investigate the reactions leading to the productions of hydrogen peroxide and nitrite ions in the medium, the gas-phase atomic and molecular radicals and radiations emitted from an AC excited Ar APPJ were measured by VUV absorption, laser induced fluorescence, optical emission spectroscopy. Moreover, the generated radicals in the aqueous-phase were measured by ESR techniques with spin-trapping. On the basis of the measurement results of reactive species, we will discuss the production pathways of hydrogen peroxide and nitrite ion in the gas-phase, aqueous-phase, and gas-liquid interface.

[1]N. Kurake *et al.*, Arch. Biochem. Biophys. **605**, 102 (2016).

8:45

DT3 3 Characterization of Reactive Species Generation in Liquid Phase by Air Plasma Effluent Exposure* KEISUKE TAKASHIMA, YUTAKA KIMURA, KEISUKE SHIMADA, KENJI NIHEI, TOSHIRO KANEKO, *Department of Electronic Engineering, Tohoku University* Generation of reactive oxygen and nitrogen species in the liquid phase, during exposure to air atmospheric pressure plasma effluent gas, is experimentally studied through reactive species measurements in gas and liquid phases. Admixture of the plasma effluent gas with the nitric oxides (NO and NO_2) resulted in the significant production of N_2O_5 and HNO_3

and consumption of ozone and NO or NO_2 measured with FT-IR in gas phase. The effects of the admixture on the reactive species in the liquid phase are also analyzed with absorption spectroscopy for nitric acids and resulted in the significant increase of the nitrite concentration. The measured short-lived species in liquid phase with chemical probes suggest the importance of the liquid phase chemical reactions near the gas-liquid interface resulted from the dissolution of the plasma effluent species into the liquid phase. The experimental analysis on the reaction pathways will be discussed along the measured reactive species in gas and liquid phases.

*This work is supported by JSPS KAKENHI Grant-in-Aid for Young Scientists (A) Grant Number 17H04817.

9:00

DT3 4 Cold plasma needle-activated ROS in liquid for cancer cell inactivation* CHUNQI JIANG, *Center for Bioelectrics & Department of Electrical and Computer Engineering, Old Dominion University* ESIN B. SOZER, *Center for Bioelectrics, Old Dominion University* SHUTONG SONG, *Center for Bioelectrics & Department of Electrical and Computer Engineering, Old Dominion University* NICOLA LAI, *Department of Electrical and Computer Engineering, Old Dominion University* SIQI GUO, P. THOMAS VERNIER, *Center for Bioelectrics, Old Dominion University* CBE PLASMA & PULSED POWER LAB COLLABORATION, CBE BIOLOGY & IMMUNOLOGY COLLABORATION, BME COLLABORATION Reactive oxygen and nitrogen species generated by atmospheric pressure, non-equilibrium plasmas in contact with liquid have been considered highly important agents in plasma medicine applications including bacterial disinfection, wound healing and cancer treatment. We report here measurements of ROS including hydroxyl radical and hydrogen peroxide in liquid exposed to nanosecond pulsed helium plasma jets in ambient air. The plasma was generated by a single needle powered by repetitive nanosecond multi-kilovolt pulses. OH radicals were measured in water as well as in biological media. Cancer cell lines including pancreatic and histiocytic lymphoma U-937 cells in suspension were inactivated after exposure to the plasma needle for less than one minute. Dependence of cell inactivation on the OH production in liquid is discussed.

*Work is supported in part by the Old Dominion University Frank Reidy Research Center for Bioelectrics and the Air Force Office of Scientific Research (FA9550-15-1-0517 & FA9550-17-1-0257).

9:15

DT3 5 Functional recovery of hypoxic ischemic encephalopathy (HIE) by plasma inhalation to living body lungs* TAKAMICHI HIRATA, HIROKI WATANABE, SAYAKA MATSUDA, CHIHIRO KOBAYASHI, AKIRA MORI, *Graduate School of Engineering, Tokyo City University* YOSHIKI KUDO, *Department of Obstetrics and Gynecology, Hiroshima University* MITSUTOSHI IWASHITA, *Department of Obstetrics and Gynecology, Kyorin University* We performed to clarify the mechanism by which the irradiation / inhalation using atmospheric-pressure plasma promotes disease treatments such as burn wound (1), lungs and heart disease (2), and recovery of hypoxic ischemic encephalopathy (HIE). Especially, from the viewpoint of brain disease treatment, we are now accomplishing the experiments concerning plasma inhalation (method of inhaling plasma flow from living body lungs) to reproduce brain cells that became dysfunction by HIE. From the result of the plasma inhalation experiments using small animals (rat), the effect of controlling brain disease was found by inhaling the gas in a mixture of the plasma flow and N_2O into the rat HIE model.

*This study was supported by a Grant-in-Aid for Scientific Research on Innovative Areas (No. 24108010) from the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT) [1,2].

[1]T. Hirata *et al.*, Jpn. J. Appl. Phys. **53**, 010302 (2014).
[2]C. Tsutsui *et al.*, Jpn. J. Appl. Phys. **53**, 060309 (2014).

SESSION ET1: PLASMAS IN LIQUIDS I

Tuesday Morning, 7 November 2017; Room: Salon D at 10:00; David Go, University of Notre Dame, presiding

Invited Papers

10:00

ET1 1 Solvated electrons and plasma – liquid chemistry in plasma exposed microdroplets*

PAUL MAGUIRE, *University of Ulster*

Transport of micron-sized liquid droplets through a low temperature atmospheric pressure RF plasma [1] has demonstrated some remarkable effects. After a short flight time, ~120 us, rapid plasma-induced nanoparticle chemical reactions have been observed, significantly faster than observed in plasma – bulk liquid studies and many orders of magnitude faster than in standard bulk chemistry. The microdroplet system allows for a controlled gas environment, a large surface area to volume ratio, very small reaction volume, low droplet temperature, in-flight chemical synthesis and encapsulation of nanoparticles, and their remote delivery. Nanoparticles can be formed without surfactant or surface ligands and can be delivered to surfaces, cells or liquid downstream. The in-droplet synthesis rate of nanoparticles was estimated to be at least 7 orders of magnitude faster than standard synthesis processes involving colloidal chemistry. It was also much faster that approaches based on microfluidic microreactors or high energy radiolysis [2]. The droplet chemistry leading to nanoparticle formation is complex. The plasma feed gas contains only noble gases along with H_2O from the evaporating droplet. Other observed chemical species in the liquid are H_2O_2 and OH, most likely due to generation of these species in the plasma phase. The H_2O_2 concentration reached 30 mM after 120 us plasma exposure. The degradation rate of Methylene Blue dye due to OH radical bombardment was observed with varying distance up to 150 mm from the plasma source. Results from radial diffusion reaction simulations will be presented.

*Funding from EPSRC acknowledged (Grants EP/K006088/1 and EP/K006142/1).

[1]P. D. Maguire *et al.*, Appl. Phys. Lett. **106**, 224101 (2015).
[2]P. D. Maguire *et al.*, Nano Lett. **17**, 1336 (2017).

Contributed Papers

10:30

ET1 2 A novel wire-to-cylinder plasma-water-setup for environmental applications KATHARINA STAPELMANN, *North Carolina State University* CAROLIN RATERING, *Ruhr University Bochum* A novel plasma-water setup was built for water treatment for environmental applications. The high-voltage electrode is a capillary, allowing different gases to be injected to the liquid. The grounded electrode is a cylindrical mesh, wrapped around a glass cylinder. As a first step, the properties of the influx of the gas are investigated optically and by Schlieren imaging. Further, the discharge behavior is investigated optically by means of CCD camera imaging and optical emission spectroscopy. The discharge behavior is correlated to the gas influx. First colorimetric investigations reveal insights to the production of chemical species, such as nitrate and nitrite. Based on terephthalate dosimetry, production and diffusion of OH radicals is observed by fluorescence measurements.

10:45

ET1 3 Studies of discharges in high conductivity liquids using fast imaging and simulations LEONIDAS ASIMAKOULAS, MOHAMMAD KARIM, TOM FIELD, BILL GRAHAM, *Queens University Belfast, Centre for Plasma Physics* LOW TEMPERATURE PLASMA GROUP TEAM Discharges can be produced in high conductivity liquid at low voltages (~300 V). Here this is achieved within a cathodic, 500 nm radius pin-to-grounded plate electrode environment. The investigation is centered around a Photron SA-X2 fast framing camera operating at between 60-100 kHz framing rates with synchronized current and voltage measurements. The discharges are observed from their light emission with no backlighting. Shadowgraphy shows they are generated in low-density regions formed close to the pin. This fine tip structure allowed confirmation of vapour growth beginning at the highest electric field gradient. The first observable bubble, with 30 um diameter, is formed at the tip within 2 microseconds of the 300 V, 60 ns rise time pulse. More bubbles then coalesce up the electrode and down from the tip. The discharges with us lifetimes are contained within the bubbles and depend on liquid's conductivity and applied voltage. A finite element analysis simulation of the vapour, electrical field and discharge behaviour will be presented. The authors want to gratefully acknowledge Prof Franta Krcma for his assistance.

11:00

ET1 4 Investigation of droplet generation induced by atmospheric pressure glow discharge in contact with liquid NAOKI SHIRAI, GOJU SUGA, SHUSUKE NISHIYAMA, KOICHI SASAKI, *Hokkaido University* Atmospheric pressure non-thermal plasma in and in contact with liquids has been studied for a wide range of applications. Although many researches have been reported about plasma using liquid electrode, the detail mechanism of the plasma-liquid interaction have not been understood completely. For example, optical emission mechanism of metal cation (such as Na^+) transported from liquid (NaCl aq.) electrode is still unclear. In this study, we focused attention on droplet generation from liquid electrode when liquid electrode discharge is generated. The droplet generation depends on optical emission from the discharge. The droplet dynamics in plasma was observed by laser light scattering. With increasing concentration of NaCl aq., amount of droplet increased and distance of scattered droplet became longer. Namely, amount of droplet depend on the concentration of NaCl aq. solution. When we use the NaCl aq. solution mixed with other electrolyte including metal cation such as $CuSO_4$, intensity of spectral emission of Cu increased compared with the case of using only $CuSO_4$ aq. solution. These results indicate that droplet generation which depends on concentration of NaCl aq. is important factor for transport of metal cation in solution to gas phase.

11:15

ET1 5 DC driven low pressure glow discharge in high water vapor content: A characterization study* MALIK TAHIYAT, TANVIR FAROUK, *Univ of South Carolina* Plasma discharge in liquid medium has been a topic of immense interest. Theoretical efforts have been pursued to get insight on physicochemical processes being influenced due to trace water vapor either present as residual or provided at known concentration. However, studies on discharge at high vapor content is limited. In this study discharge characteristics of plasma in high water concentration (>90%) is investigated experimentally for pressure range of 1–15 Torr to maximize vapor loading without condensation. Voltage-current characteristics was obtained over 0-14 mA of current for each operating pressure; current density was determined to ensure normal glow regime of operation. Spatially resolved optical emission spectroscopy was also conducted to determine OH, O, H_2 and H distribution in the interelectrode separation. The normalized intensities of OH and O emission lines are found to be more prominent in positive column, whereas the emission lines of H are most intense in cathode glow region. The electric field distribution along the discharge gap was also measured. We envision that data obtained from this characterization study will also provide valuable data for validation of plasma kinetic schemes associated with water vapor.

*This research is being performed using funding received from the DOE Office of Nuclear Energy's Nuclear Energy University Programs. Award Number: DE-NE0008273 NEUP Project 14-7730.

11:30

ET1 6 A Multiphase Computational Model for Non-Equilibrium Plasma Discharge in Gas Bubbles Immersed in Liquid ASHISH SHARMA, DMITRY LEVKO, LAXMINARAYAN RAJA, *University of Texas at Austin* Plasma generated by electrical discharges in gas bubbles suspended in liquids has found application primarily in liquid fuel reforming and plasma combustion. It is important to resolve the plasma discharge in both gas and liquid phases to accurately capture the physics of this discharge. Hence, in this work, we present a computational model for non-equilibrium plasma discharge in liquid phase and extend the existing computational framework for plasma discharge in gases to include both liquid and gas phases. The computational model is based on the self-consistent, multispecies continuum description of the plasma and solves the governing equations in both liquid and gas phases simultaneously. This new model considers the variations in the conductivity of the liquid dielectric for a more realistic description of the plasma discharge. The model also allows transport of charged and neutral species between gas and liquid phases through the bubble surface, where the transport terms in the liquid phase consists of both drift and diffusion terms.

11:45

ET1 7 Kinetic and graph-theoretic approaches to model plasmas in liquids* TOMOYUKI MURAKAMI, *Seikei University* THOMAS J MORGAN, LUTZ HUWEL, *Wesleyan University* WILLIAM G GRAHAM, *Queen's University Belfast* Plasma interaction with gas-liquid interfaces is be-coming increasingly important in biological applications. The numerical and theoretical works to be presented here focus on general plasma initiated chemistry in gas-liquid interfaces. Two different approaches, a kinetic theory and a graph theory are used to model the complex chemistry. To describe the plasma-dynamics in the water vapor layer, a time-dependent 1-D numerical simulation combined with the detailed chemical kinetic model has been developed. Furthermore, the chemical reactions are analyzed using graph theory. Since the chemistry is complicated enough for the formation of web-like networks, we can identify which species play central roles to trigger subsequent reactions.

*This work was partly supported by JSPS KAKENHI Grant Number 16K04998.

SESSION ET2: MODELING AND SIMULATION I

Tuesday Morning, 7 November 2017
Room: Duquesne at 10:00
Jannis Teunissen, University of Leuven - KU Leuven, presiding

Contributed Papers

10:00

ET2 1 PIC-DSMC Model For Breakdown In Voids* LAURA BIEDERMANN, CHRIS MOORE, CHRISTIAN TURNER, *Sandia National Laboratories* High-voltage components such as transformers, gas vacuum switches, wide-bandgap power electronics, and power LEDs may be externally coated with polymer encapsulants to prevent surface flashover and high voltage breakdown. These epoxies and silicon resin encapsulants may be poured into a mold or dispensed as a liquid encapsulant to surround the component. During the thermal/vacuum cure process, potentially-damaging air voids may be introduced in the epoxy from entrapped air or partial delamination. Such microscopic voids can be an initiation point for high-voltage breakdown. We have developed atmospheric air models for breakdown [1] within such atmospheric voids as are found in encapsulated transformers. Plasma development and voltage collapse are simulated using an electrostatic particle-in-cell (PIC) code that models particle-particle collisions using the direct simulation Monte Carlo (DSMC) method. We model the breakdown of ~25-μm voids including surface charging and plasma-surface interactions such as photoemission, sputtering, and SEE. These models show under what conditions (voltage, location) voids can induce high voltage breakdown.

*Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC. for the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-NA-0003525.

[1]C. H. Moore *et al.*, ICOPS (2016).

10:15

ET2 2 Student Excellence Award Finalist: Gas Breakdown: Across Length Scales and Frequency* AMANDA LOVELESS, ADAM DARR, ALLEN GARNER, *Purdue University* Paschen's law (PL), based on the Townsend avalanche criterion, is a well-established condition for gas breakdown. Reducing gap sizes to microscale leads to deviations from PL that are hypothesized to arise due to ion enhanced field emission. We summarize a matched asymptotic analysis that quantifies the transition from field emission to Townsend avalanche to the classical PL. As device miniaturization further drives dimensions to nanoscale, the impact of surface roughness on field emission and length scales on the order of the electron mean free path will further alter the gas breakdown condition. We couple the one-dimensional Schrödinger equation to the microscale breakdown equation to estimate the conditions at which quantum effects become dominant. Finally, we assess the impact of frequency on gas breakdown, showing the transition of breakdown predictions from DC to RF to microwave conditions and deriving universal, analytic equations that demonstrate the relative insensitivity of the right-hand side of Paschen's curve to frequency. Implications of the results and the ultimate connection to microwave breakdown and other breakdown regimes, such as space-charge limited and streamers, will be discussed.

*Funded by an NRC Faculty Development Grant and an IEEE DEIS Graduate Fellowship (AML).

Invited Papers

10:30

ET2 3 Modeling and Simulation of Lightning Related Transient Luminous Events at High Altitude in the Earth's Atmosphere

VICTOR PASKO, *Penn State University*

Transient luminous events are large-scale optical events occurring at high altitude in the Earth's atmosphere, which are directly related to the electrical activity in underlying thunderstorms. Several different types of transient luminous events have been documented and classified. These include relatively slow-moving fountains of blue light, known as 'blue jets', that emanate from the top of thunderclouds up to an altitude of 40 km; 'sprites' that develop at the base of the ionosphere and move rapidly downwards at speeds up to 10,000 km/s; 'elves', which are lightning induced flashes that can spread over 300 km laterally, and upward moving 'gigantic jets', which establish a direct path of electrical contact between thundercloud tops and the lower ionosphere. This presentation focuses of the modeling efforts at Penn State directed on interpretation of morphological electrical gas discharge features observed in sprite events. After a brief review of similarity properties of electrical discharges as a function of gas pressure, we introduce parameters typically used for quantitative description of electron avalanches and discuss importance of space charge effects on different spatial scales, including sprite halos (exhibiting 10s of km transverse extents) and sprite streamers (requiring sub-meter resolution for accurate description). A special emphasis is placed on interpretation of initiation and development of sprite streamers captured in high-speed video observations and critical review of the recent modeling efforts related to these observations.

Contributed Papers

11:00

ET2 4 Striation Characteristics in Radio-Frequency Capacitively Coupled Discharges under Different Conditions KALLOL BERA, SHAHID RAUF, JOHN FORSTER, KEN COLLINS, *Applied Materials, Inc.* In radio-frequency (RF) capacitively coupled discharges, striations with spatial periodic structure have been observed. Thermoelectric effect that reduces electron energy diffusion has been proposed [1] as a mechanism generating the periodic structure. The thermoelectric coefficient is calculated using Bolsig+ [2], and incorporated in our fluid plasma model. Two- and three-dimensional modeling of RF capacitive discharge is first done without thermoelectric effect. The charged species densities are then randomly perturbed, and the growth or decay of different modes with time is observed. Multiple peaks in electron density are formed in an almost periodic manner. The result shows that N_2 plasma with weaker thermoelectric effect is more stable than Ar plasma. With increase in secondary electron emission from the electrodes, plasma peaks intensify. Magnetic field increases plasma peaks at lower pressure. For a design with multiple steps on the electrode, distance between plasma peaks is modified. In addition, the striation characteristics are modified by pressure, electrode spacing, rf power and rf pulsing. Compared to two-dimensional model, plasma peaks are stronger in three-dimensional model.

[1]Mackey *et al.*, Appl. Math. Lett. (2005).

[2]Hagelaar and Pitchford, Plasma Sources Sci. Technol. (2005).

11:15

ET2 5 Student Excellence Award Finalist: Differences between Cartesian and spherical 1d3v Particle-In-Cell simulations SEBASTIAN WILCZEK, JAN TRIESCHMANN, JULIAN SCHULZE,* RALF PETER BRINKMANN, *Ruhr University, Bochum, Germany* ZOLTAN DONKO, *Wigner Research Centre for Physics, Budapest, Hungary* THOMAS MUSSENBROCK, *Brandenburg University of Technology, Cottbus, Germany* 1d3v Particle-In-Cell (PIC) simulations of capacitively coupled radio frequency (CCRF) discharges are usually considered to be symmetric, which implies a Cartesian grid is used. However, in most CCRF systems the driven electrode is smaller compared to the grounded electrode (grounded chamber walls have to be taken into account). In such a situation, different current fluxes at both electrodes can be observed and a DC self-bias develops. The plasma boundary sheaths at the driven and grounded electrode exhibit different dynamics (e.g. sheath potential and sheath size). Especially in very asymmetric scenarios, most of the RF power is coupled into the plasma at the smaller driven electrode. In order to investigate such an asymmetric electrode configuration within 1d3v PIC simulations, a spherical grid is implemented. In this work, the differences between symmetric and asymmetric 1d3v PIC simulations of CCRF discharges are investigated. Particularly, the electron power gain and loss mechanisms (e.g. nonlinear electron resonance heating, power gain due to secondary electrons, ambipolar heating) are studied for different discharge conditions.

*West Virginia University, Morgantown, USA.

11:30

ET2 6 Electric field rebound of He plasma jets with positive and negative polarities on metal and dielectric targets PEDRO VIEGAS, *LPP, Ecole Polytechnique, Palaiseau, France* ADAM OBRUSNIK, ZDENEK BONAVENTURA, *Faculty of Science, Masaryk University, Brno, Czech Republic* ANNE BOURDON, *LPP, Ecole Polytechnique, Palaiseau, France* In this work, simulations performed with a 2D fluid discharge model coupled with detailed kinetic schemes and flow calculations address the study of the dynamics of a helium plasma discharge with N_2 or O_2 admixtures propagating in a dielectric tube. At the exit of the tube, the discharge propagates as a free jet or interacts with a metallic or dielectric target, grounded or at a floating potential. The spatial distribution of the gas mixture at the exit of the tube is previously obtained through the flow calculation of helium flowing through the tube into the outside air. After the arrival of the ionization front at a target, the interaction is shown to be dependent on the features of the target and a rebound of electric field in both positive and negative polarities is observed in some cases. We focus on the calculation of electric field associated to plasma propagation in the tube and in the plasma plume, to gas-mixing at the end of the tube, to the interaction with the target and to the rebound, in different conditions (electrode inside or outside the tube, location of the target) for both positive and negative polarities. The characteristics of the electric field rebound and its dependence on the presence of target and on the type of target are studied in detail.

11:45

ET2 7 Kinetic, Unstructured Finite Element PIC-DSMC Simulation of Ultra-Fast Pin-to-Plane Discharge in Air* CHRISTOPHER MOORE, ANDREW FIERRO, *Sandia Natl Labs* JEAN-MICHEL POUVESLE, ERIC ROBERT, *CNRS/Université d'Orléans* ANNE BOURDON, *CNRS/Polytechnique* ROY JORGENSON, ASHISH JINDAL, MATTHEW HOPKINS, *Sandia Natl Labs* Recently, highly reproducible breakdown experiments in air at atmospheric pressure, leading to large volume homogeneous plasmas, have been performed in a 1.5 cm gap, pin-to-plane geometry with $\sim$2 ns rise-time [1]. The present work compares temporally resolved experimental results for the electric field and electron density to kinetic simulations using an unstructured finite element Particle-In-Cell code that models the collisions via Direct Simulation Monte Carlo. The model includes electron-neutral elastic, excitation, ionization, and attachment collisions; ion and photon induced electron emission from surfaces; ion-neutral collisions; and self-absorption, photoionization, and photodissociation. The model tracks excited state neutrals which can be quenched through collisions with the background gas and surfaces or spontaneously emit a photon (isotropically) and transition to a lower state.

*Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-NA0003525.

[1]J.-M. Pouvesle *et al.*, "Experimental Study of an Ultra-Fast Atmospheric Pressure Discharge in a Pin-to-Plate Geometry", ICOPS 2017.

SESSION ET3: PLASMA ETCHING FOR SEMICONDUCTOR PROCESSING

Tuesday Morning, 7 November 2017; Room: Oakmont Junior Ballroom at 10:00; SangHeon Song, Lam Research, presiding

Invited Papers

10:00

ET3 1 Etching for New Devices*

KEIZO KINOSHITA, *Photonics Electronics Technology Research Association*

Information network and services are now one of the most important social infrastructure. They have been growing by progression of LSI devices. An important characteristic of the LSI device is function extendibility by integrating new materials and new device concepts. Plasma processes are key fabrication technologies of the LSI devices, and have been confronted to meet various requirements. Two topics will be presented here. First topic is Silicon Photonics (SiPh) which is a newly-proposed device for data communications. It has come to reality by applying the CMOS process technology on optical devices. However, there are points to be modified. One is nanometer-order control of line-edge-roughness at a very wide Si waveguide patterning. An ArF immersion lithography and a gate etching technique for 55 nm technology node and after were applied to fabricate a 440-nm-wide Si waveguide [1]. Low optical propagation loss of 0.5 dB/cm was achieved. The other is a light source integration on the SiPh device. A MEMS deep etching process was applied to fabricate a pedestal to mount a laser diode chip [2]. Second topic is magnetic material integration to realize MRAM. We need to deposit a multilayered transition metal/oxide stack film by PVD, and fabricate magnetic dot array with a few tens of nanometers in diameter without deteriorating magnetic properties. However, chemical modifications of the materials are indispensable to proceed reactive ion etching. To overcome this issue, a recovery process by reductive chemistry was proposed as an after treatment of the methanol plasma etching, and obtained comparable performances with an Ar ion etched non-damage sample [3].

*This work was supported by NEDO.

[1]S.-H. Jeong *et al.*, Opt. Express **21**, 30163 (2013).
[2]K. Kinoshita *et al.*, AVS 63rd Symp., PS-ThP18 (2016).
[3]K. Kinoshita *et al.*, Jpn. J. Appl. Phys. **51**, 08HA01 (2012).

Contributed Papers

10:30

ET3 2 Cryogenic etching: A solution for damage-free narrow trench etching* QUANZHI ZHANG, STEFAN TINCK, ANNEMIE BOGAERTS, *University of Antwerp* Porous materials are commonly used in microelectronics, as they can meet the demand for continuously shrinking electronic feature dimensions. However, they are facing severe challenges in plasma etching, due to plasma induced damage. A hybrid Monte Carlo-fluid model is employed to investigate cryogenic C_4F_8 plasma etching of porous materials. It is shown that the plasma induced damage gradually decreases with lowering the substrate temperature, which allows that C_4F_8 condenses inside the pores. Negligible plasma induced damage can be achieved around −110 °C. However, the etching rate is reduced due to the pore filling with C_4F_8. The simulation results of both etching rate and plasma induced damage as a function of wafer temperature are validated by experimental results, performed at imec.

*We acknowledge the support from Marie Skodowska-Curie actions (Grant Agreement-702604).

10:45

ET3 3 Machine Learning of Micro/macro Cavity Data for Etching Recipe Optimization HYAKKA NAKADA, MASARU KURIHARA, MASAYOSHI ISHIKAWA, TATEHITO USUI, NAOYUKI KOFUJI, TAKESHI OHMORI, *Hitachi, Ltd. Research & Development Group* Semiconductor manufacturing processing has been complexed and the process development period has been prolonged with the progress of device structure from 2D to 3D. The long development period causes the increase of the device cost. In plasma etching process, a set of the control parameters of etcher is called as recipe. Rapid optimization of the recipe to obtain a target profile has been required to reduce the development period. A recipe exploration method based on machine learning of feature data related to etching profile is developed to accelerate the recipe optimization. Micro/macro cavity method [1] is used to extract the feature data. An approximately region to obtain a vertical etching profile as a target can be determined in the feature data space because the feature data show the characteristics of ion assist etching and radical etching. The correlation between the feature data and recipes is learned by a machine learning model. The recipes for the vertical profile are predicted by the learning model. Three recipes to etch the vertical profile were found from only seven times of Si trench etching using the recipes predicted by the learning of 60 sets of the feature data.

[1]K. Watanabe and H. Komiyama, J. Electrochem. Soc. **137** (1990).

Invited Papers

11:00
ET3 4 Atomic Layer Etch: A Concurrent Plasma Modeling and Process Approach
MINGMEI WANG, *TEL Technology Center, America LLC*

Atomic layer etching (ALE) has been investigated over decades and is getting more attention recently than ever due to its potential capability of solving grand challenges in advanced node plasma etch. As feature size shrank to nanometer scale, etch issues such as ARDE, loading, etch stop, top clogging etc. turned to be more severe than in more relaxed patterning schemes. However, ALE, as a promising solution to all problems in traditional etch methods, has its own challenges. Questions that are frequently asked regarding self-limiting process, productivity, hardware capability, etc. have to be considered during an ALE process development. To precisely control ALE processes, fundamental understanding of the surface interactions during etch is required. In this talk, we will discuss concurrent engineering approaches including both modeling and experiment to understand and develop ALE etching processes that meet grand challenge requirements. The core of the approach is an integrated chamber scale HPEM (Hybrid Plasma Equipment Model)-feature scale MCFPM (Monte Carlo Feature Profile Model) model [1]. The concurrent engineering approach comprises stages of development and prediction capability tests using both blanket wafer and patterned stack data and finally process parameter optimization. By using this approach, we are able to provide insights on how to resolve grand challenges in plasma etch with a minimum of engineering resources. The presentation will survey both experimental and computational results representing a few case studies in SAC quasi-ALE, Si ALE, Si3N4 ALE, etc. Furthermore, insights into the relationship between chamber function and critical surface interactions will be discussed.

[1]M. Wang and M. Kushner, J. Appl. Phys. **107** (2010).

Contributed Papers

11:30
ET3 5 Selective Etching by Tailored RF Ion Energy Control Using Frequency/Phase Locked RF Power Delivery YUSUKE YOSHIDA, *TEL Technology Center, America, LLC* DAVID COUMOU, SCOTT WHITE, *MKS Instruments, Inc.* STEVEN SHANNON, *Nuclear Engineering Department, North Carolina State University* SERGEY VORONIN, *TEL Technology Center, America, LLC* ALOK RANJAN, *Tokyo Electron Miyagi, Ltd.* The control of the ion energy distribution function (IEDF) for surface interaction remains a vexing challenge for semiconductor process engineers. Exploiting frequency and phase locked RF power delivery for sheath voltage manipulation presents a unique method for ion energy control. By regulating the skew of the ion energy distribution, we achieve improved fidelity of etch rate control. Experimental sputtering and etch yields for oxide and nitride films are obtained from measured IEDFs and etch rate data. By tailoring the ion energy peak location and the overall shape of the IEDF, we preferentially "delegate" more ions to the optimal ion energy group while minimizing the surface material impingement of other energy bands. This ability to customize IEDFs yields a process enhancement for precise material removal compared to conventional techniques, offering a great potential for etch applications at atomic scale (say ALE) processes.

SESSION FT1: INDUCTIVELY COUPLED PLASMAS
Tuesday Afternoon, 7 November 2017
Room: Salon D at 13:30
Peter Ventzek, Tokyo Electron Ltd., presiding

Contributed Papers

13:30
FT1 1 Theoretical investigation of power balance and hysteresis of a miniature microwave ICP-plasmajet MICHAEL KLUTE, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum, Germany* HORIA-EUGEN PORTEANU, WOLFGANG HEINRICH, *Microwave Department, Ferdinand-Braun-Institut, Germany* PETER AWAKOWICZ, *Electrical Engineering and Plasma Technology, Ruhr University Bochum, Germany* RALF PETER BRINKMANN, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum, Germany* Microwave-driven plasmas-jets offer attractive properties for various technical applications. They are usually operated in a capacitive mode. However, experimental experience shows a number of disadvantages for capacitive coupling such as high boundary sheath voltage and thus high electrical losses. Due to these characteristics, inductively coupled plasmas are of particular interest for technical applications. Recently *Porteanu et al.*[1] proposed a small scale plasma-jet operated as an inductive discharge. The key characteristic of the suggested plasma-jet is the implementation of an LC-resonance-circuit into a cavity resonator. In this work the proposed plasma-jet is examined theoretically. A global model for the electromagnetic fields and energy balance is presented. Mathematical analysis of the electromagnetic fields leads to a description based on a sum of different modes. It is found that the modes of zero and first order can be identified with inductive and capacitive coupling. In a second step the matching network and its frequency depended characteristic are taken into account. Finally an investigation of possible hysteresis effects is carried out.

[1]Porteanu *et al.*, Plasma Sources Sci.Technol. **22**, 035016 (2013).

13:45
FT1 2 Experimental Investigation of pulsed inductively coupled Ar and Ar/N2 plasmas by a time-resolved Langmuir probe* FEI GAO, YU-RU ZHANG, YONG-XIN LIU, YOU-NIAN WANG, *Dalian University of Technology* Pulsed inductively coupled plasmas have been widely used in the etching process of the semiconductor manufacturing due to its many advantages, such as more flexible control of the ion energy distribution. The time evolutions of the radial distribution of electron density and electron energy probability function (EEPF) are measured in pulsed inductively coupled Ar and Ar/N_2 plasmas by using a Langmuir probe. In Ar discharge, the electron density generally exhibits a parabolic distributions during the whole active-glow period at a low pressure. However, at a high pressure, the electron density first increases and then decreases with the increase of the radial distance during the initial active-glow. As

the time evolves, the peak of the electron density gradually moves towards the chamber center, and finally the radial distribution of electron density tend to be parabolic during the late active-glow period. In Ar/N_2 discharge, the maxima of the electron density is off-centered during the whole active-glow. In addition, the peak of electron density in Ar/N_2 discharge occurs earlier than that in pure Ar discharge. To better understand the underlying physics, the radial distribution of the EEPF are analyzed.

*This work was supported by the National Natural Science Foundation of China (NSFC) (Grant No. 11675039), and the Fundamental Research Funds for the Central Universities (Grant No. DUT16LK06).

14:00

FT1 3 Fundamental Studies of Pulsed Processing Plasmas KRISTOPHER FORD, JOEL BRANDON, *North Carolina State University* KYUNG SUN KIM, *Samsung Electronics Co.* TYLER LIST, TIANYU MA, PRIYANKA ARORA, *University of Houston* SHUO HUANG, *University of Michigan* SANG KI NAM, *Samsung Electronics Co.* STEVEN SHANNON, *North Carolina State University* VINCENT DONNELLY, *University of Houston* MARK KUSHNER, *University of Michigan* SAMSUNG PLASMA TECHNOLOGY JOINT RESEARCH LABORATORY COLLABORATION Pulsed plasmas present new opportunities for semiconductor processing, which include unique chemistries, reduced substrate heating, and decreased charge damage. Transient plasmas also present new challenges compared to constant power delivery systems due to their dynamic behavior. Power delivery, diagnostics, and simulation tools must provide μs-scale time resolution and response. System measurement and control on this time scale not only ensures repeatable process conditions; it also enables new process control and optimization methods. This work reviews time resolved characterizations efforts on inductively coupled plasmas that focus on system characterization, chemistry, and plasma surface interaction using an array of diagnostics (optical emission, Langmuir probe, microwave hairpin, fast CCD imaging, RF measurement) along with pulsed RF simulation in the HPEM framework. Time resolved measurements of n_e, T_e, V_p, V_f, V_{RF}, I_{RF}, and optical emission will be presented together with simulation cases. From these studies, compelling pathways for transient plasma control and optimization will be presented.

14:15

FT1 4 Model Describing The E-H Mode Transition With Intrinsic Electrical Properties Of Inductively Coupled Plasma Reactors SHAUN SMITH, DAVID J. COUMOU, *MKS Instruments, Inc.* For inductively coupled plasma sources, there exists a minimum operating power, below which, the plasma source abruptly shifts from the inductive coupling mode. This transition point for an RF driven ICP is from the electrostatic mode to the electromagnetic mode, or more commonly referred to, as the E-H mode transition. For increasing current, the power absorbed during E-mode precipitously *drops* toward a minimum defined by a power loss boundary, similar to that seen in a toroidal plasma source. After the transition to H-mode, the plasma current *increases* the power absorbed by the plasma source. For pattern transfer, the E and H modes both serve selectivity and etch benefits, however the mode transition remains a vexing challenge for RF power delivery systems. The existence of the E-H mode transition is well known in RF inductively coupled plasmas, but has not been extended to toroidal plasma sources. We present a self-consistent electrical description of the mechanism for the E-H mode transition. We show the transition point can be intentionally manipulated with the variation of an electrical property of the system. Commensurate with model experimental results, we describe the impact the E-H mode imposes on RF power delivery coupled to ICP reactors.

14:30

FT1 5 E-H mode detection and symmetry effects in ICP plasmas with bias power MICHAEL KLICK, *Plasmetrex GmbH* ICP based plasma etchers are widely used in the semiconductor industry. Parameters from industrial chambers are usually not suited to detect different plasma modes. Here the Self Excited Electron Resonance Spectroscopy (SEERS) is extended to provide parameters which describe the electron heating and the symmetry of the plasma. During ignition and at lower power the plasma in a ICP chamber is in the E-mode. With increasing RF power the electron density increases, the inductive heating becomes more efficient. The investigations were focused on the dependency of the transition on the chamber hardware, pressure, ICP power, and phase angle in two commercial ICP chambers. The E-H mode transition is clearly identified and it shows a well pronounced dependence on the pressure. Due to the chamber geometry, the plasma shows a different symmetry in E and H mode. In the H mode at high source power, substrate and bias power play no role and the plasma shows the classical asymmetry. A phase shift shows a larger impact on the transition than the pressure. At lower source power, the power coupling at the driven substrate electrode dominates → no influence of phase shift. One chamber shows always an earlier transition - indicating here a higher efficiency of the inductive power coupling system.

14:45

FT1 6 Effects of electron energy probability function on the negative ion production in low pressure inductively coupled hydrogen plasmas* WEI YANG, *Dalian University of Technology, China and Princeton Plasma Phys Lab* HONG LI, FEI GAO, *Dalian University of Technology, China* ALEXANDER KHRABROV, IGOR KAGANOVICH, *Princeton Plasma Phys Lab* YOU-NIAN WANG, *Dalian University of Technology, China* Dissociative attachment of low energy electrons to vibrationally excited hydrogen molecules plays a key role in the formation of volume negative hydrogen ions. The vibrationally excited hydrogen molecules are generated in collisions with fast electrons, while negative ions are generated in collisions with low energy electrons.[1] Therefore, the generation of negative hydrogen ions greatly depends on the electron energy probability function (EEPF) The effects of EEPF on the negative ion production are investigated in low-pressure inductively coupled hydrogen plasmas. The particle species, i.e., ground-state hydrogen molecules and atoms, 14 vibrationally excited molecules, positive ions, negative ions and electrons, accompanied by the relevant chemical reactions, are included in the model. The plasma parameters, i.e., temperatures of the electrons and H atoms and number densities of all species, as a function of gas pressure, are evaluated for different EEPFs. To validate the model, the calculated EEPFs and the electron density and temperature are compared with experimental measurements; and a reasonable agreement between simulated plasma parameters and experimental data is achieved.

*Work supported by National Magnetic Confinement Fusion Science Program, China (Grant No. 2015GB114000).

15:00

FT1 7 Circuit induced pulsed RF transients: impact on plasma parameters and source design considerations* JOEL BRANDON, KRIS FORD, *North Carolina State University* SANG-KI NAM, JANG-GYOO YANG, SANGHEON LEE, *Samsung Electronics* STEVE SHANNON, *North Carolina State University* The transient characteristics of pulse-modulated inductively coupled plasmas in argon are experimentally investigated. Time resolved measurements are made by Langmuir probe and microwave hairpin probe for a cylindrical ICP configuration driven at 13.56MHz with nominal peak power densities between 0.01 W/cm^3 – 0.1 W/cm^3 and nominal 1 kHz pulse frequency. Optimized conjugate match tuning to plasma impedance at a defined time after pulse initiation provides control of the initial n_e and T_e transient comparable to generator-driven pulse shaping methods at the expense of non-optimal time averaged reflected power. Source design considerations can also contribute to time dependent control of power delivery, particularly when tuning strategies such as delivered power leveling and agile frequency control are considered. Time resolved measurement of plasma parameters and power dissipation in the system are presented, demonstrating control of n_e and T_e rise times through matching network and source topology design, controlling rise time by as much as a factor of four and enabling within-pulse power delivery control.

*This work funded with generous support from Samsung Electronics.

15:15

FT1 8 A novel linear microwave plasma source using circular TE_{11} mode and continuous line slot antenna JU-HONG CHA, HO-JUN LEE, *Department of Electrical Engineering, Pusan National University, Busan, South Korea* For conventional linear microwave plasma sources with co-axial TEM waveguide, there is relatively large resistive loss in inner conductor of the waveguide. The wave electric field is directed normal to the quartz window surface, which enhances electron loss. To improve performances of linear microwave plasma sources, a novel linear microwave plasma source suitable for large area deposition and etching processing has been developed. In the proposed plasma source, circular TE_{11} mode has been used for plasma generation. After mode conversion from rectangular TE_{10} to circular TE_{11}, 2.45 GHz microwave power is transferred to plasma via continuous line slot antenna along the wave propagation direction. The direction of radiated electric field is almost parallel to the quartz window. Diagnostics on the basic plasma properties using electrical probe and microwave cutoff probe confirmed that proposed source has better plasma generation efficiency compared with the conventional source. For 200 mTorr Ar plasma with 1 kW microwave input power, plasma density improvement about 80% was achieved. In addition, more stable impedance matching characteristics has been observed in proposed plasma source.

SESSION FT2: PLASMA BOUNDARIES AND SHEATHS

Tuesday Afternoon, 7 November 2017
Room: Duquesne at 13:30
Scott Baalrud, University of Iowa, presiding

Contributed Papers

13:30

FT2 1 Modeling wall ion fluxes in an RF discharge: insights from 2D PIC simulation ROMAIN LUCKEN, *Laboratoire de Physique des Plasmas, UMR CNRS/Ecole polytechnique* TREVOR LAFLEUR, *Laboratoire de Physique des Plasmas, UMR CNRS/Ecole polytechnique, Centre National d'Études Spatiales (CNES) Toulouse* VIVIEN CROES, ANTOINE TAVANT, *Laboratoire de Physique des Plasmas, UMR CNRS/Ecole polytechnique, Safran Aircraft Engines, Electric Propulsion Unit* ANNE BOURDON, PASCAL CHABERT, *Laboratoire de Physique des Plasmas, UMR CNRS/Ecole polytechnique* Global models of plasma discharges have been widely used to simulate plasma reactors in the fields of plasma processing and space propulsion [Chabert *et al.* 2012, Grondein *et al.* 2016]. These models rely on accurate description of the ion current leaving the plasma: after undergoing a pre-sheath drop, the ions enter the sheath at Bohm velocity. The pre-sheath drop is characterized by an edge-to-center plasma density ratio h_L and heuristic models were formerly derived to understand how this parameter varies with plasma temperatures and ion mean free path, based on one-dimensional (1D) transport theory [1], and validated by 1D simulation [2]. A model of inductively coupled plasma (ICP) discharges was implemented into a 2D benchmarked particle-in-cell (PIC) code [3], running with various gases (Ar, He, Xe). These simulations show that the ion flux has a strong spatial dependency – in agreement with former results [Lafleur *et al.* 2012] – and that it is affected by the aspect ratio of the discharge reactor. The influence of dielectric walls is also investigated.

[1]Chabert *et al.*, (2011).
[2]Lafleur *et al.*, (2015).
[3]Turner *et al.*, (2012).

13:45

FT2 2 Student Excellence Award Finalist: 3D ion and neutral distribution measurements and simulations of the boundary region of a magnetized plasma* DEREK S. THOMPSON, *West Virginia University, Department of Physics* SHANE KENILEY, RINAT KHAZIEV, DAVIDE CURRELI, *University of Illinois at Urbana-Champaign, Department of Nuclear, Plasma, and Radiological Engineering* M. UMAIR SIDDIQUI, *Phase Four, Inc.* MIGUEL F. HENRIQUEZ, DAVID D. CARON, ANDREW J. JEMIOLO, JACOB W. MCLAUGHLIN, MIKAL T. DUFOR, LUKE A. NEAL, EARL E. SCIME, *West Virginia University, Department of Physics* We present the first paired 3D laser induced fluorescence measurements of ion and neutral velocity distribution functions (I/NVDFs) in a plasma boundary. These measurements are performed in the presheath region of an absorbing boundary immersed in a background magnetic field that is obliquely incident to the boundary surface ($\psi = 74°$). Parallel and perpendicular flow measurements demonstrate that cross-field flows occur and that ions within several gyro-radii of the surface are accelerated in the $\vec{E} \times \vec{B}$ direction. We present electrostatic probe measurements of electron temperature, plasma density, and electric potential in the same region. Ion, neutral and electron measurements are compared to particle-in-cell and Boltzmann simulations, allowing direct comparison between measured and theoretical distribution functions for all three species.

*NSF PHYS 1360278.

Invited Papers

14:00

FT2 3 Hot Cathode Current Mode Transitions*
MICHAEL CAMPANELL, *Lawrence Livermore Natl Lab*

Hot cathodes are a key component of many plasma physics experiments and applications. Examples include thermionic converters, thermionic tethers, emissive probes, neutralizers (e.g. in thrusters), and the Large Plasma Device. In the literature, it is often assumed that when the thermionic current is limited, the sheath is "space-charge limited" (SCL) and ions accelerate into the cathode [1]. In recent studies we showed that SCL sheaths cannot exist at floating surfaces because charge-exchange (CX) ion trapping in the virtual cathode forces a transition to a state with an inverse sheath [2]. In this talk, we show on theoretical grounds, and with continuum kinetic simulation videos, that stable SCL sheaths cannot exist at biased hot cathodes either. Whenever a virtual cathode first forms, CX ions will start collecting at the potential minimum until the ion density reaches the electron density at a point. Further ion collection makes the new neutral region grow from the cathode sheath towards the anode, leading to the creation of another plasma where ions are confined and both electrodes have inverse sheaths. The transitions from temperature-limited mode to anode glow mode seen in previous experiments [3,4] and PIC simulations [4] of thermionic discharges are consistent with this explanation. We conclude that the existence of operating modes with inverse cathode sheaths needs to be considered for other plasma applications that rely on hot cathodes.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This work was supported by LDRD 17-LW-059.

[1]S. Takamura *et al.*, Contrib. Plasma Phys. **44**, 126 (2004).
[2]M. D. Campanell and M. V. Umansky, Phys. Rev. Lett. **116**, 085003 (2016); Phys. Plasmas **24**, 057101 (2017).
[3]L. Malter, E. O. Johnson, and W. M. Webster, RCA Review **12**, 415 (1951).
[4]F. Greiner *et al.*, Phys. Rev. Lett. **70**, 3071 (1993).

TUESDAY AFTERNOON \ FT2

Contributed Papers

14:30

FT2 4 Charge-exchange ions in a weakly collisional sheath UWE CZARNETZKI, TSANKO TSANKOV, *Institute for Plasma and Atomic Physics, Ruhr University Bochum* The interaction of plasma ions with surfaces is determined by their velocity distribution function (IVDF). The IVDF is formed primarily in the sheath region in front of the surface. Here, an approximate approach is presented for a weakly collisional sheath that relies on an expansion of the ion velocity distribution function. The expansion is based on the smallness parameter sheath width to ion mean free path. With this approach the distribution function of the ions colliding in the sheath is estimated. This allows accurate prediction of various ion characteristics in the sheath (mean ion energy, effective ion temperature, ion mean velocity). Results for a floating sheath and a high-voltage sheath are presented.

14:45

FT2 5 Transition in sheath structure near emissive grooved surface in discharge plasma controlled by electron beam* IRINA SCHWEIGERT, *George Washington University, Washington, DC, 20052* T. S. BURTON, G. B. THOMPSON, *The University of Alabama, Tuscaloosa, AL, 35487* S. LANGENDORF, M. L. R. WALKER, *Georgia Institute of Technology, Atlanta, Georgia, 30332* M. KEIDAR, *George Washington University, Washington, DC, 20052* The plasma/sheath characteristics, particularly the transition between different types of sheath near the grooved plate made from hBN was studied in the experiment and kinetic simulation. The discharge plasma is sustained by an electron beam from the emissive heated cathode. These beam electrons provide the secondary electrons emission from the grooved plate placed with some distance from the cathode. In the experiment, the critical voltage for 'collapse of sheath' was measured for a planar surface and grooved surfaces for a 1 mm and 5 mm grooved depth. The 2d3V PIC MCC simulations were performed for the experimental conditions. The measured response of sheath structure near the grooved emissive surface on the change of discharge voltage shows an increase the critical voltage with grooved depth. In the 2d3V PIC MCC simulations, the collapse voltage was obtained with an increase of groove depth which is in good agreement with experimental data. It was shown in simulations that the increase of critical voltage for grooved surface is attributed to a variation of the potential distribution near the grooved surface and the redistribution of electron flux from the plasma to the plate.

*The authors gratefully acknowledge FA9550-11-1-0160.

15:00

FT2 6 Stability of the plasma sheath in the presence of secondary electrons emission* ROBERTO MARTORELLI, VIVIEN CROES, ROMAIN LUCKEN, ANTOINE TAVANT, TREVOR LAFLEUR, ANNE BOURDON, PASCAL CHABERT, *Ecole Polytechnique* PLASMA FROIDS, LABORATOIRE DE PHYSIQUE DES PLASMAS (LPP) TEAM We propose a systematic analysis of the structural stability of the sheath in the presence of secondary electron emission induced by energetic plasma electron impacting the wall. The analysis is performed using the Sagdeev potential, in a similar fashion as in the study of nonlinear ion-acoustic waves. In this context, the study of the Poisson's equation for the sheath potential is reduced to an initial value problem. Setting the proper initial conditions, corresponding to the electric field and the electrostatic potential at the wall, different possible solutions for the sheath potential can be obtained, from Bohm-like to oscillatory ones. The main characteristics of the classical monotonic sheath can be reproduced as well through this approach. The inclusion of the emitted electrons provides additional degrees of freedom to the system, specifically the density and the energy of the emitted electrons. We show that a transition between different types of solutions might be induced by changing the value of the parameters of the system. In particular we are able to reproduce a transition to a non-monotonic sheath for critical values of the parameters, in a similar fashion as in the space charge limited regime.

*CHEOPS.

15:15

FT2 7 Spatiotemporal analysis of the electric field reversals in capacitively coupled SiH_4/Ar RF discharge* WANG XIFENG, JIA WEN-ZHU, SONG YUAN-HONG, DAI ZHONGLING, WANG YOU-NIAN, *School of Physics, Dalian University of Technology, Dalian* PSEG TEAM A capacitively coupled RF SiH_4/Ar discharge is investigated by a fluid/MC hybrid model, in which we focus our main attention on the influences of gas ratio, pressure and voltage amplitude on the electric field reversals. It is found that as a small proportion of SiH_4 is added in Ar discharge, a weak reverse electric field is obtained near the collapse sheath edge, mainly due to the accumulation of electrons on account of drift and ambipolar diffusion. Results show that electrons might be heated by the reverse fields during the sheath contraction. However, these heated electrons are not sufficient for background gas ionization. As the SiH_4 ratio increases, the electron field reversal is enhanced apparently and becomes the dominate electron heating method, contributing to high energy tails of electron energy probability functions (EEPFs) which would be responsible for significant ionization at sheath collapse phase. Further, the electric field reversal could be enhanced by increasing the pressure and voltage, leading to an enhanced heating compared with that in a pure Ar discharge.

*National Natural Science Foundation of China (Grant No. 11275038 and 11675036).

SESSION FT3: HEAVY PARTICLE COLLISIONS

Tuesday Afternoon, 7 November 2017; Room: Oakmont Junior Ballroom at 13:30; Larry Viehland, Chatham University, presiding

Invited Papers

13:30

FT3 1 New type of asymmetries in two-center interferences observed in ion-molecular collisions*

XINWEN MA, *Institute of Modern Physics, Chinese Academy of Sciences*

In ion-atom collisions, the atomic version of double-slit experiments has been proposed by using two atomic centers as the double slits [1]. Recently, various two-center interference effects have been observed in different reaction channels such as ionization [2], capture [3], and the dissociative ionization [4]. These studies significantly advanced our knowledge of the double-slit interference in elastic processes. However, almost all studies so far focused on the interference effects rising from homo-diatomic molecules. Recently, we experimentally studied the interference effects in double capture collisions of He^+ on the hetero-diatomic molecule CO where the molecule played the role of an asymmetric 'double-slit', and the interference effects were examined in the molecular orientation spectra. It was found that, different from the homo-DM, the angular distributions of the hetero-DM present significant asymmetry. Such asymmetry of the interference pattern suggests certain phase of the ion collision processes has been mapped to the double-slit phase term. Therefore, atomic "double-slit" interference can be exploited to experimentally extract the phase information of ion collision processes and, furthermore, the methodology can be potentially used to manipulate the ion collision interactions. In this conference, we will report on such phenomena and the detailed analysis of the phase.

*National Key Research and Development Program of China, the National Natural Science Foundation of China, the Chinese Academy of Sciences.

[1]T. F. Tuan and E. Gerjuoy, Phys. Rev. **117**, 756 (1960).
[2]N. Stolterfoht *et al.*, Phys. Rev. Lett. **87**, 023201 (2001).
[3]L. P. H. Schmidt *et al.*, Phys. Rev. Lett. **101**, 173202 (2008).
[4]S. F. Zhang *et al.*, Phys. Rev. Lett. **112**, 023201 (2014).

14:00

FT3 2 The effect of projectile wave packet width on the fully differential ionization cross sections*

LADISLAU NAGY, *Babes-Bolyai University*

In the last years a debate arose concerning the effect of the projectile coherence on the fully differential ionization cross sections in ion-atom impact. Some experimental data show, that the measured cross sections depend on the coherence width of the wave packet associated to the projectile. However, other experiments did not reveal such an effect. The goal of the present paper is to perform a systematic study on the dependence of the cross section on the coherence properties of the projectile. In the theory of atomic collisions there are two alternative ways in describing the ionization by fast ion projectiles. The impact parameter (or the semiclassical) model, assumes a classical trajectory of the projectile, and treats with quantum mechanics only the electrons. The other model, based on quantum scattering theory, includes also the projectile into the quantum system. In this model usually it is assumed that the projectile wave packet in momentum space is sufficiently well peaked about its mean momentum, and a plane wave with infinite coherence width is associated to the projectile. In the present model we have assigned to the projectile a wave packet with a Gaussian profile characterized by a finite coherence width. The position of the wave packet's centre is obtained on the basis of classical scattering. The scattering amplitude is calculated as an inverse Fourier transform of the impact parameter dependent probability amplitude, weighted by the Gaussian profile of the projectile. We study the dependence of the cross sections on the wave packet's width for the ionization of helium by fast ions (100 MeV/amu C^{6+} and 3 MeV protons). The results of our calculations support the importance of the projectile coherence effects in fully differential cross section measurements.

*This study was done in collaboration with Ferenc Járai-Szabó and Sándor Borbély.

Contributed Papers

14:30

FT3 3 Student Excellence Award Finalist: Fully Differential Study of Capture with Vibrational Dissociation in p + H_2 Collisions

BASU LAMICHHANE, *Missouri University of Science & Technology* THUSITHA ARTHANAYAKA, *Columbia Astrophysics Laboratory* JUAN REMOLINA, *University Of Michigan* AHMAD HASAN, *Dept. of Physics, UAE University, Al Ain, Abu Dhabi, UAE* MARCELO CIAPPINA, *Institute of Physics, Academy*

of Sciences of the Czech Republic, Dolní Břežany, Czech Republic FRANCISCO NAVARRETE, RAUL BARRACHINA, *Centro Atómico Bariloche and Instituto Balseiro, Bariloche, Río Negro, Argentina* RAMAZI LOMSADZE, *Tbilisi State University, Tbilisi 0179, Georgia* MICHAEL SCHULZ, *Missouri University of Science & Technology* In recent years, the important role of the projectile coherence properties has been confirmed in several studies on ion-atom scattering processes. In the present study, we used such coherence effects as a tool to sensitively study the few- body dynamics of the scattering process. To this end, a kinematically complete experiment on dissociative capture in 75 Kev p + H_2 collisions was performed. Fully differential cross-sections (FDCS) were extracted for a kinetic energy release of 1 eV and for two different molecular orientations as a function of scattering angle. The experiment was performed with a coherent and incoherent projectile beam. The coherent to incoherent FDCS ratios, which represents the interference term, revealed two different types of interference, single- and two-center interference. In the latter an unexpected phase shift of π was found in the pronounced oscillations observed in the interference term. This phase shift will be discussed in context of data reported by other groups for other processes in similar collision systems.

14:45

FT3 4 Controlled charge exchange between alkaline earth metals and their ions* ROBIN COTE, *University of Connecticut* We theoretically investigate the prospects of realizing controlled charge exchange via magnetic Feshbach resonances in cold and ultracold collisions of atoms and ions. In particular, we focus on near-resonant charge exchange in heteroisotopic combinations of alkaline earth metals. We focus our discussion on Be + Be^+ and Ca + Ca^+. Alkaline-earth elements exhibit favorable electronic and hyperfine structure. The quantum scattering calculations are performed for a range of initial states and experimentally attainable magnetic fields in coupled-channel Feshbach projection formalism, where higher-order corrections such as the mass-polarization term are explicitely included. In addition, we predict a number of magnetic Feshbach resonances for different heteronuclear isotopic combinations of the listed and related alkaline earth elements. Our results imply that near-resonant charge-exchange could be used to control charge diffusion and mobility in cold samples.

*Partial funded by MURI US Army Research Office Grant No. W911NF-14-1-0378.

15:00

FT3 5 Charged Particle Dynamics using the Path Integral Technique* A L HARRIS, T A SAXTON, Z TEMPLE, *Illinois State University* We present a theoretical and computational technique for calculating time dependent wave functions using the path integral method. Unlike other methods, we calculate the quantum mechanical time evolution operator numerically exactly and use it to time evolve an initial state wave function. To demonstrate the success and accuracy of the method, we present numerical results for simple one-dimensional systems, such as the harmonic oscillator and a particle moving under a constant force. We show that our numerical results agree with the known analytical answers. One of the primary advantages of the path integral method is that it will work better for more massive particles. We test this idea by comparing results for both an electron and a proton, and show that the calculation is much more efficient for heavier particles. This property makes the path integral method ideal for the future study of heavy-ion atomic collisions.

*Work supported by NSF Grant PHY-1505217.

15:15

FT3 6 Testing A Dual-anode Miniature Electron Beam Ion Trap For The Production Of Highly Charged Ions AUNG NAING, *University of Delaware* JOSEPH TAN, *National Institute of Standards and Technology* In addition to the central role that highly charged ions (HCI) play in the study of radiative and collisional processes occurring in laboratory and astrophysical plasmas, recent theoretical studies indicate that certain HCI, such as Pr^{9+} and Nd^{10+}, are potentially useful for interesting applications, such as the development of next-generation atomic clocks, quantum information, or the search for variation in the fine-structure constant [1]. Highly charged ions can be produced in an electron beam ion source/trap (EBIS/T) with a strong magnetic field (~3 T). However, lower magnetic fields are more suitable for abundantly producing the proposed candidate ions with ionization thresholds ranging from 100 eV to 2000 eV. We are developing a room-temperature miniature EBIT (mini-EBIT) for improving the production of such ions. A dual-anode design is suited to the lower electron beam energy compatible with the production of such ions by compensating for the space charge effects. This work presents new features in the design and the construction of the mini-EBIT. Progress on the production of HCI in the mini-EBIT is presented.

[1]M. Safronova *et al.*, PRL **113**, 030801 (2014).

SESSION GT1: POSTER SESSION I
Tuesday Afternoon, 7 November 2017
Exhibit Salon ABC at 16:00

GT1 1 Deep minimum in the Coulomb-Born TDCS for electron-impact ionization of atomic hydrogen S.J. WARD, J. B. KENT, *University of North Texas* Recently, Macek *et al.* attributed a deep minimum in the triply differential cross section (TDCS) for electron impact ionization of helium to a vortex [1]. Vortices have been shown to be present for positron-impact ionization of atomic hydrogen [2]. Using the Coulomb-Born approximation [3] we have obtained a deep minimum in the TDCS for electron-impact ionization of atomic hydrogen for an incident energy of 76.45 eV and for the doubly symmetric coplanar geometry. At the scattering angle where there is a minimum in the TDCS, the real and imaginary parts of the transition matrix element are zero.

[1]J. H. Macek, J. B. Sternberg, S. Y. Ovchinnikov, and J. S. Briggs, Phys. Rev. Lett. **104**, 033201 (2010).
[2]F. Navarrete and R. O. Barrachina, J. Phys. B **48**, 055201 (2015).
[3]J. Botero and J. H. Macek, Phys. Rev. A **45**, 154 (1992).

GT1 2 Comprehensive out-of-plane (e, $2e$) measurements on He autoionizing levels* N.L.S. MARTIN, B.N. KIM, C.M. WEAVER, *University of Kentucky* B.A. DEHARAK, *Illinois Wesleyan University* O. ZATSARINNY, K. BARTSCHAT, *Drake University* We report out-of-scattering-plane (e, $2e$) measurements on helium $2\ell2\ell'$ autoionizing levels for 80, 100, 120, 150, and 488 eV incident electron energies, and scattering angles 60°, 50.8°, 45°, 39.2°, and 20.5°, respectively. The kinematics are similar in all cases: ejected electrons are detected in a plane that contains the momentum transfer direction and is perpendicular to the scattering plane, and the momentum transfer is 2.1 a.u. [1]. The results are presented as (e, $2e$) angular distributions energy-integrated over each level, and are compared with our second-order theory calculated for 488 eV incident electron energy, as well as predictions based on a fully non-perturbative close-coupling model. At all energies except 80 eV, the shapes of the angular distributions, and the recoil peak intensities, are in excellent agreement with the 488 eV results for all three autoionizing levels. The reasons why this is so, for incident energies that vary by almost a factor of five, is at present unclear.

*This work was supported by the National Science Foundation under Grants Nos. PHY-0855040, PHY-1607140 (NLSM), PHY-1402899 (BAd), and PHY-1403245 (KB).

[1]B. A. deHarak, K. Bartschat, and N. L. S. Martin, Phys. Rev. Lett. **100**, 063201 (2008).

GT1 3 Introducing a phase factor for the two-electron continuum representation LORENZO UGO ANCARANI, *Universite de Lorraine, Metz, France* A.S. ZAYTSEV, S.A. ZAYTSEV, *Pacific National University, Khabarovsk, Russia* We propose a numerical approach to describe three-body Coulomb continuum wave functions in the entire space. The key idea is to use an expansion on a basis set of functions whose asymptotic behavior is as close as possible to the formal one in the Ω_0 region where all interparticle distances are large. The proposed basis set contains two ingredients. First, it uses two-particle functions, named Convoluted Quasi Sturmian (CQS) [1]. While these behave asymptotically as a six-dimensional outgoing (incoming) spherical wave, they miss out an important Coulomb logarithmic phase which corresponds to the interelectronic potential; truncated expansions on CQS functions failed to converge satisfactorily with increasing basis size [2]. This brings us to the second ingredient, which consists in introducing – from the outset – an appropriate phase factor into the basis set. These dressed CQS functions possess then an asymptotic behavior closer to the formal one, and one then obtains a satisfactory convergence of the partial transition amplitudes on a basis set of reasonable size. Choosing a suitable phase factor, we demonstrate this numerically for the two-electron continuum that occurs, for example, in the electron-impact double ionization of helium; we consider typical experimental kinematical conditions in which two electrons escape with 10 eV each.

[1]A. S. Zaytsev, L. U. Ancarani, and S. A. Zaytsev, Eur. Phys. J. Plus **131**, 48 (2016).
[2]A. S. Zaytsev, L. U. Ancarani, and S. A. Zaytsev, Eur. Phys. D in press (2017).

GT1 4 Electron impact single ionization of ammonia LORENZO UGO ANCARANI, *Universite de Lorraine, Metz, France* CARLOS MARIO GRANADOS-CASTRO, *Martin-Luther-Universitat Halle-Wittenberg, Germany* ALESSANDRO GENONI, *Universite de Lorraine, Metz, France* Recent (e,2e) measurements on polyatomic molecules motivated the development of theoretical methods to calculate and describe ionization cross sections in their most differential form. In this contribution, we study the electron impact single ionization of the outer valence orbital $3a_1$ of NH_3. In a one-active electron approach, we use Generalized Sturmian Functions (GSF) [1] to expand the scattering wave function; having an appropriate asymptotic outgoing-type behavior, the basis functions are particularly efficient and allow the scattering amplitude to be extracted directly from the asymptotic behavior of the scattering solution (essentially the expansion coefficients) without the need of calculating a transition matrix element. To describe the initial state wave function, we use either the one-center wave function calculated by Moccia [2], or the one obtained by a DFT calculation. The molecular potential is either the one obtained through a static exchange approximation or the one of the DFT approach. The comparison between the two allows us to separate out the importance of the molecular structure quality from the numerical description of the molecular single continuum. We also compare our triple differential cross sections (TDCS) with the recent measurements [3].

[1]C. M. Granados-Castro and L. U. Ancarani, Eur. J. Phys. D **71**, 65 (2017).
[2]R. Moccia, J. Chem. Phys. **40**, 2176 (1964).
[3]R. El Mir *et al.*, J. Phys. B **48**, 175202 (2015).

GT1 5 Proton-helium double ionization: exploring different momentum-transfer regimes LORENZO UGO ANCARANI, *Universite de Lorraine, Metz, France* A.I. GOMEZ, G. GASANEO, *Universidad Nacional del Sur, Bahia Blanca, Argentina* M.J. AMBROSIO, *Kansas State University, Manhattan, USA* D.M. MITNIK, *IAFE, CONICET-UBA, Argentina* We present a systematic study of fully differential cross sections (FDCS) for the double ionization of helium by fast proton impact, considering different kinematic conditions going from intermediate momentum transfers up to within the impulsive regime. Our formalism treats the projectile-target interaction up to first order, but the intra-target ones to all orders. Within this framework, we deal with a first order three-body nonhomogeneous equation whose driven term depends parametrically on the momentum transfer. We solve it numerically with a Generalized Sturmian Function approach [1,2], and the ionization transition amplitude is extracted directly from the asymptotic range of the scattering wavefunction for the perturbed target. Our approach yields satisfactory agreement with the relative data measured for protons impinging with 6 MeV [3]. We explore how the binary, recoil and back-to-back structures in the FDCS change with the excess energy and momentum transfer.

[1]M. J. Ambrosio *et al.*, Phys. Rev. A **92**, 042704 (2015).
[2]M. J. Ambrosio *et al.*, Eur. Phys. J. D **71**, 127 (2017).
[3]D. Fischer *et al.*, Phys. Rev. Lett. **90**, 243201 (2003).

GT1 6 Partial Wave Contributions in Oriented Collisions* A L HARRIS, *Illinois State University* S AMAMI, *Missouri University of Science and Technology* T A SAXTON, *Illinois State University* D H MADISON, *Missouri University of Science and Technology* We present fully differential cross sections (FDCS) for two collision processes with oriented atoms. The first collision is electron-impact ionization of oriented Mg (3p), and the second collision is electron-impact excitation-ionization of helium with an oriented final state $He^+(2p0)$ ion. Surprisingly, the theoretical functional form of the FDCS is the same for both processes, despite the fact that the only physical similarity is an oriented excited state in both processes. We use the common theoretical functional form to explore possible physical similarities between the two processes. The contributions to the FDCS of individual partial waves of the ionized electron and projectile are examined, and we show that for the ionization of oriented Mg, the FDCS are dominated by larger partial waves of the ejected electron. For the excitation-ionization process, the FDCS is dominated by the $L = 2$ partial wave.

*Work supported by NSF Grants PHY-1505217 and PHY-1505819.

GT1 7 Two-Dimensional Potential Scattering using the Path Integral Technique* A L HARRIS, T A SAXTON, Z TEMPLE, *Illinois State University* We have previously developed a path integral technique for the calculation of time-dependent wave functions using a numerically exact quantum mechanical propagator. This

TUESDAY AFTERNOON \ GT1

method was applied to particles moving in one dimension, and was shown to work well for heavy particles. We have now extended our method to charged particles moving in two dimensions. Here we present numerical results that demonstrate the accuracy and efficiency of the method. We also explore the necessary numerical parameters and discuss applications to heavy-ion atomic collisions.

*Work supported by NSF Grant PHY-1505217.

GT1 8 Ionization of Lithium using the HI-5 Model* A L HARRIS, J LYON, A PLUMADORE, M BATES, *Illinois State University* The study of heavy-ion collisions with atoms is an increasingly active area of collision physics. We introduce the Heavy-Ion 5-Body (HI-5) model for charged particle collisions, which is only recently possible due to improvements in computing capabilities. Using our model, we present fully differential cross sections for inner and outer shell ionization of lithium using heavy-ion projectiles. Results are compared to other theoretical models, and the role of electron correlation is studied.

*Work supported by NSF Grant PHY-1505217.

GT1 9 Proton collisions with water clusters studied with a screened independent atom model* TOM KIRCHNER, *York University* HANS JÜRGEN LÜDDE, *Goethe University Frankfurt* The independent atom model purports that electron emission from molecules can be calculated by combining atomic cross sections. The simplest realization of this idea is the additivity rule according to which the molecular cross section is obtained as the sum of the atomic cross sections for all atoms that make up the molecule. Recently, we introduced a model in which the simple sum is replaced by a weighted sum. The weight factors are determined from an exact calculation of the effective area that is obtained when surrounding all atoms in the molecule by spheres representative of the atomic cross sections and projecting the resulting structure on the plane that is perpendicular to the projectile beam. The calculation is carried out using a pixel counting method [1]. In this contribution, we use this approach to study proton collisions with water clusters $(H_2O)_n$, n=1...10. A recent theoretical work found that at 100 keV impact energy the electron transfer cross section σ_n^{cap} for n=1...6 is proportional to $n^{2/3}$ [2]. By contrast, we find $\sigma_n^{cap} \propto n$ at 100 keV, while at 10 keV $\sigma_n^{cap} \propto n^{2/3}$ is obtained.

*Work supported in part by NSERC, Canada.

[1]H.J. Lüdde *et al.*, Eur. Phys. J. D **70**, 82 (2016).
[2]A. J. Privett *et al.*, PLoS ONE **12**, e0174456 (2017).

GT1 10 Analysis of radiative emissions in O^{6+}-argon, -water, and -methane charge-exchange collisions* ANTHONY C. K. LEUNG, TOM KIRCHNER, *York University* Charge exchange between highly-charged (solar wind) ions and neutrals is the main mechanism responsible for the observed x-ray emission from comets. A recent joint experimental/theoretical work looked at these processes for O^{6+} collisions with argon atoms and a variety of molecules including water and methane at impact energies which correspond to the low and high solar wind speeds [1]. In the present work we study these collision systems using the two-center basis generator method within the independent electron model [2]. For the molecular targets we used a spectral representation of the target Hamiltonian and found that a closure approximation was necessary to produce reliable total cross section results for single-, double-, and triple-electron transfer. For the single-electron transfer channel we carried out a radiative cascade analysis and compared the resulting emission spectra with the classical-trajectory Monte Carlo calculations reported in [1]. Overall, the agreement is satisfactory.

*Work supported by SHARCNET, OGS, and NSERC, Canada.

[1]J. R. Machaceket *al.*, Astrophys. J. **809**, 75 (2015).
[2]A. C. K. Leung and T. Kirchner, Phys. Rev. A **95**, 042703 (2017).

GT1 11 Electron impact ionization of Methane at intermediate energy* ESAM ALI, *Missouri Univ of Sci & Tech* ZEHRA OZER, *Department of Physics, e-COL Laboratory, Afyon Kocatepe University, 03200, Afyon, Turkey* CHUANGANG NING, *Department of Physics, State Key Laboratory of Low-Dimensional Quantum Physics, Tsinghua University, Beijing 100084, China* JAMES COLGAN, *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA* MEVLUT DOGAN, *Department of Physics, e-COL Laboratory, Afyon Kocatepe University, 03200, Afyon, Turkey* DON MADISON, *Missouri Univ of Sci & Tech* We have investigated the triple differential cross sections (TDCSs) for the electron impact ionization of the $1t_1$ state of molecular CH_4 at 250 eV for asymmetric coplanar geometry with the scattering angles of 10°, 20°, and 25° at fixed ejected energies 30 eV and 50 eV. The experimental measurement are compared to molecular 3-boday distorted wave (M3DW), where the theory used two different calculations by using proper average (M3DW-PA) and orientation averaged molecular orbital (M3DW-OAMO) approximation. The theory predicts the shape and the structure of cross section for experiment. Overall, the M3DW-PA show better shape agreement with experiment more than OAMO calculations.

*This work was supported by NSF.

GT1 12 Theoretical and experimental study of electron impact ionization (e,2e) of the R-Carvone molecule for an intermediate incident electron energy* ESAM ALI, *Missouri Univ of Sci & Tech* DARRYL JONES, *School of Chemical and Physical Sciences, Flinders University, GPO Box 2100, Adelaide SA 5001, Australia* JAMES COLGAN, CHUANGANG NING, *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA* ODDUR INGÃ3LFSSON, *Science Institute and Department of Chemistry, University of Iceland, Dunhagi 3, 107 Reykjavik, Iceland* MICHAEL BRUNGER, *School of Chemical and Physical Sciences, Flinders University, GPO Box 2100, Adelaide SA 5001, Australia* DON MADISON, *Missouri Univ of Sci & Tech* We will present preliminary results from a combined theoretical and experimental study of electron impact single ionization of the R-Carvone molecule. The study was performed for a 250 eV incident electron energy, an ejected electron energy of 20 eV, and for three fixed scattered electron angles (5°, 10°, and 15°) in asymmetric coplanar geometry. Experimental data were measured for the three unresolved outermost orbitals - the highest, next highest, and next-next highest occupied molecular orbitals (HOMO, NHOMO, and HOMO-2). The generation of fully differential cross sections for this large molecule is extremely challenging for both experimental measurements and theoretical calculations. Theoretical M3DW (molecular 3-body distorted wave) results are summed over the three unresolved states to enable the comparison with the experimental data.

*This work was supported by NSF.

GT1 13 Fully Differential Study of Dissociative Capture and Coulomb explosion in p + H_2 Collisions BASU LAMICHHANE, MADHAV DHITAL, *Missouri University of Science and Technology* THUSITHA ARTHANAYAKA, *Columbia Astrophysics Laboratory* AHMAD HASAN, *Dept. of Physics, UAE University, Al Ain, Abu Dhabi, UAE* KRISHNA KOIRALA, TREVOR VOSS, *Missouri University of Science and Technology* RAMAZI LOMSADZE, *Tbilisi State University, Tbilisi 0179, Georgia* MICHAEL SCHULZ, *Missouri University of Science and Technology* We measured fully differential cross sections (FDCS) for dissociation due to capture and excitation to a repulsive state as well as Coulomb explosion due to double electron capture in p+H_2 collisions. FDCS were analyzed for various molecular orientations relative to the momentum transfer in the transverse direction (q_x) as a function of projectile scattering angle (θ_p). Two orientations parallel and perpendicular to q_x were analyzed. For the latter orientation two-center interference was identified. For the dissociative case, data were obtained for a range of kinetic energy releases (KER) from 5eV to 11eV. In this region the $2p\pi_u$ and the $2s\sigma_g$ states mainly contribute to dissociation. The interference pattern observed is consistent with the $2s\sigma_g$ state being dominant at large θ_p while at small θ_p both states contributes significantly. In double capture case, KER between 13eV to 27eV were selected since here only one channel (Coulomb explosion) contributes and the KER determines the inter-nuclear separation, the phase angle should be well determined. Nevertheless, the observed interference pattern is significantly less pronounced than for dissociation.

GT1 14 Atomic data of low-charged Sn ions for lithography applications* JAMES COLGAN, D. P. KILCREASE, J. ABDALLAH, M. E. SHERRILL, C. J. FONTES, P. HAKEL, *Los Alamos National Laboratory* Sn is one of the most promising materials that has been investigated to date in the quest to make intense radiation sources for EUV lithography. Sn plasma readily produces an intense, narrow, emission band around 13.5 nm, a feature that has long been studied in efforts to exploit this useful property. The efforts to predict the properties of Sn that produce these intense emission features are complicated by the complex atomic structure of the Sn ions in question. We have begun investigations into the opacity of Sn at low temperatures. We have explored the accuracy of some approximations used in opacity models for Sn. The use of intermediate-coupling, as compared to full configuration-interaction (CI), is not adequate to obtain accurate line positions of the important bound-bound transitions in Sn. One requires full CI to properly describe the strong mixing between the various n=4 sub-shells that give rise to the Δn=0 transitions that dominate the opacity spectrum at low temperatures. Calculations that include full CI for large numbers of configurations quickly become computationally prohibitive, so we have explored hybrid calculations, in which full CI is retained only for the most important transitions [1].

*The Los Alamos National Laboratory is operated by Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under Contract No. DE-AC5206NA25396.

[1]J. Colgan *et al.*, HEDP **23**, 133 (2017).

GT1 15 Influence of a biased electrode on the electron energy distribution function* S.D. BAALRUD, *Univ of Iowa* B. YEE, E.V. BARNAT, M.M. HOPKINS, *Sandia National Laboratory* Positively biased electrodes can influence the electron energy distribution function (EEDF) by providing a sink for low energy electrons that would otherwise be trapped. In hot filament generated discharges, the EEDF typically consists of a cool trapped population at energies below the energy associated with ions sheaths at the chamber wall and a comparatively warm tail population associated with the filament primaries. Inserting a positively biased electrode has little influence if it is sufficiently small. However, as the electrode area approaches $\sqrt{2.3m_e/m_i}A_w$, where A_w is the chamber wall area, it collects most of the total electron current exiting the plasma. This can dramatically reduce the density of the otherwise trapped population, and cause the electron temperature to increase as the distribution approaches a temperature associated with the energetic filament primaries. A global model is developed, which shows the interconnected nature of the electron temperature, density and the plasma potential. The model is compared with Langmuir probe measurements in a dc filament generated plasma [1], and with new 2D PIC simulations.

*This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under Contract DE-AC04-94SL85000.

[1]Barnat, Laity, and Baalrud, Phys. Plasmas **21**, 103512 (2014).

GT1 16 Ion flow and sheath structure near positively biased electrodes* RYAN HOOD, BRETT SCHEINER, SCOTT BAALRUD, *University of Iowa* MATTHEW HOPKINS, ED BARNAT, BENJAMIN YEE, *Sandia National Laboratories* ROBERT MERLINO, FRED SKIFF, *University of Iowa* Measurements of the ion velocity distribution function and plasma potential were made near small positively biased electrodes using laser-induced fluorescence and an emissive probe [1]. The effect of dielectric material surrounding the electrode was tested and compared with a 2D particle-in-cell simulation. Both measurements and simulation reveal that if the electrode is embedded within a dielectric ring, ions are accelerated toward the electrode to approximately 0.5 times the ion sound speed before being deflected radially by the electron sheath potential barrier. The axial potential profile in this case contains a virtual cathode. In comparison, when the surrounding dielectric is removed, both the ion flow and virtual cathode are almost completely absent. These measurements suggest that the ion presheath from the negatively charged dielectric encapsulates the electron sheath of the positively biased electrode, resulting in a virtual cathode that substantially influences the local ion flow profile.

*This research was supported by the Office of Fusion Energy Sciences at the U.S. Department of Energy under contract DE-AC04-94SL85000.

[1]R. Hood, B. Scheiner, S. D. Baalrud, M. M. Hopkins, E. V. Barnat, B. T. Yee, R. L. Merlino, and F. Skiff, Phys. Plasmas **23**, 113503 (2016).

GT1 17 Steady-State Properties of Low Pressure Anode Spots BRETT SCHEINER, SCOTT BAALRUD, *Univ of Iowa* EDWARD BARNAT, MATTHEW HOPKINS, BENJAMIN YEE, *Sandia National Laboratories* When a small electrode is biased sufficiently above the plasma potential, the electron impact ionization of neutral species near the electrode becomes significant. At neutral gas pressures of 1-100 mTorr, it has been previously observed that if this ionization rate is sufficiently high a double layer may form near the electrode. In some cases the double layer will move outward, separating a high-potential plasma attached to the electrode surface from the bulk plasma. This phenomenon is known as an anode spot. A model has been developed to describe the steady-state properties of anode spots. In the model, an analysis of current loss, power balance, and particle balance leads to a prediction of the anode spot size, double layer potential, and form of the sheath at the electrode. These steady-state properties are related by and vary with the energy dependence of the electron impact ionization cross section, a feature absent in prior descriptions of the anode spot.

GT1 18 A real-time model for secondary electron emission coefficients in low temperature plasmas* MANASWI DAKSHA, *West Virginia University* JULIAN SCHULZE, *Ruhr University Bochum, West Virginia University* Low temperature plasmas are an indispensable tool in the processing of highly technical devices. However, the predictive power on the behavior of such plasmas is limited. This is, in part, due to plasma-surface interactions. In modeling such plasmas, it is important to know the electron sticking and the ion-induced secondary electron emission coefficient. Experimental determination of secondary electron emission coefficients (SEEC) is difficult at low ion energies. Therefore, there is only a few amount of metals and metal-oxides that have determined coefficients for a small set of surface conditions. A theoretical model is required to predict and explain these coefficients for a wide range of materials and conditions. Here, SEECs due to potential auger emission are calculated ab initio. They are calculated for metal-oxides and metals with varying surface conditions. These conditions include plane orientation and crystallinity. Furthermore, many gases are considered including argon and oxygen. Excellent agreement is found between experiment and theory for metals. The theory predicts the secondary electron emission to vary widely depending on the metal-oxide crystal structure and purity. This has been found to be true experimentally for magnesium oxide.

*US NSF Grant No. 1601080.

GT1 19 Experimental observations on the characteristics of an anode spot onset* EDWARD BARNAT, *Sandia National Laboratories* BRETT SCHEINER, SCOTT BAALRUD, *University of Iowa* BEN YEE, MATT HOPKINS, *Sandia National Laboratories* Experimental observations of the characteristic features of anode spot onset and stabilization in response to a stepped voltage applied to an anode immersed in a low pressure (100 mTorr) helium afterglow are reported in this poster presentation. These observations include spatial and temporal evolution of metastable species measured by planar Laser induced fluorescence (PLIF), electron densities as measured laser-collision induced fluorescence (LCIF) and electric fields around and in the spot as measured by laser-induced fluorescence-dip (LIF-dip) spectroscopy. Oscillations observed during spot formation process are correlated to transient response of the host plasma induced by sudden loss of electron species by the spot. Experimental observations are compared with computational simulations and theory presented in a companion poster.

*This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under Contracts DE-AC04-94SL85000 and DE-SC0001939.

GT1 20 Ion extraction process from a decaying plasma by introducing an external electron source HE-PING LI, JIAN CHEN, HENG GUO, DONG-JUN JIANG, MING-SHENG ZHOU, *Tsinghua University* DEPARTMENT OF ENGINEERING PHYSICS TEAM Ion extraction is a complex physical process with multi-particle and multi-field coupling, and is important in many fields, such as materials processing, etching and some pulsed processing with plasmas induced by an intense laser. Under such a typical pulsed processing, plasmas are usually decaying; and thus, it is indispensable to develop the novel methods to improve the extraction efficiency and shorten the extraction time. However, due to the shielding effects of the electrode sheath, the electric field cannot penetrate the whole plasma region, and only the ions in the sheath can be accelerated, which limits significantly the improvement on the ion extraction efficiency for a conventional parallel-plate ion extraction process. In this study, a novel method by introducing an external electron source is proposed to weaken the shielding effects. The modeling results show that the introduction of the external electrons can implement the loss of the plasma electrons and restrain the charge separation. Under such conditions, the conventional Child-Langmuir sheath will not form, and the ion extraction time will be shortened significantly resulting from the weakening of the shielding effects of the sheath.

GT1 21 Locking the Plasma Potential with an Anodic Surface* MATTHEW HOPKINS, BENJAMIN YEE, EDWARD BARNAT, *Sandia National Laboratories* SCOTT BAALRUD, BRETT SCHEINER, *University of Iowa* It is often assumed that a small positively biased electrode immersed into a bulk plasma has negligible impact on the bulk plasma properties, including the plasma potential. This is an assumption in many diagnostic devices, such as a Langmuir probe. In this poster we present a detailed study including simulations and experiments to determine the size scales when such an immersed positive interface has non-negligible impact on the plasma [1]. That is, we answer the question, "what is the largest size for an anodic surface before it influences the plasma?". Letting $\mu = \sqrt{2.3 m_e/m_i}$, we find that if the ratio of anode area (A_A) to grounded wall area (A_W) $A_A/A_W 1 \times \mu$, we can expect little impact on the bulk plasma, but as $A_A/A_W \to 1.7 \times \mu$ we see significant influence, and at $A_A/A_W 1.7 \times \mu$, we expect the plasma potential to become locked to, and therefore controlled by, the anode potential.

*This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under Contract DE-AC04-94SL85000.

[1]Hopkins, Yee, Baalrud, and Barnat, Phys. Plasmas 23, 063519 (2016).

GT1 22 Analytical model of the short argon arc* ALEXANDER KHRABRY, IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory, Princeton, NJ* VALERIAN NEMCHINSKY, *Keiser University, Fort Lauderdale, FL* ANDREI KHODAK, *Princeton Plasma Physics Laboratory, Princeton, NJ* In a short atmospheric-pressure arc (with several millimeters between electrodes) near-electrode non-equilibrium regions may occupy major part of the inter-electrode gap or even overlap. Therefore non-equilibrium effects in plasma such as thermal, ionization non-equilibrium, electron diffusion, thermal diffusion and effects of space-charge sheaths are important for understanding of the arc physics. An analytical model of argon arc comprising of models for near-electrode regions, arc column and a model of heat transfer in cylindrical electrodes has been developed. The model predicts arc voltages, plasma density and temperature profiles and heat fluxes to the electrodes. Parametric studies of the arc have been performed for a range of the arc current density and pressure. Analytical solutions have been compared with simulation results performed making use of non-equilibrium one-dimensional arc model. The model was validated against experimental data and verified by comparison with Ref. [1].

TUESDAY AFTERNOON \ GT1

Good agreement between the analytical model and simulations and reasonable agreement with experimental data were obtained.

*Research supported by the U.S. Department of Energy (DOE), Office of Science, Fusion Energy Sciences (FES).

[1]N. Almeida *et al.*, J. Phys. D: Appl. Phys. **41** (2008).

GT1 23 Properties of the electron sheath in low temperature plasmas* BENJAMIN YEE, *Sandia National Laboratories* BRETT SCHEINER, SCOTT BAALRUD, *University of Iowa* EDWARD BARNAT, MATTHEW HOPKINS, *Sandia National Laboratories* The preponderance of sheath research has focused on ion sheaths and neglected electron sheaths in spite of their importance to Langmuir probes, microdischarges, sheath inversion, and negative ion sources. The conventional view of the electron sheath is that of a sharp transition region from the quasineutral plasma to the space charge dominated region. This view implies that only the random thermal flux of electrons crossing the electron sheath boundary is collected by the electrode. In this work, a combination of experiments, simulations, and theory is used to demonstrate that reality is considerably more complex than expected and that the physics of electron sheaths is unexpectedly rich. Advanced laser diagnostics prove the existence of a large transition region outside of the electron sheath. Simulations show that these "electron presheaths" are driven by pressure gradients rather than the electric field, and that these gradients originate from a loss cone-like truncation of the electron velocity distribution function. The electron flow driven by this pressure gradient can be sufficiently strong so as to excite instabilities in the sheath edge.

*This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under Contract DE-AC04-94SL85000.

GT1 24 On the influence of parasitic capacitances on the ion energy bombardment in a large-area multi-frequency CCP* STEFAN RIES, JULIAN SCHULZE, PETER AWAKOWICZ, *AEPT, Ruhr University Bochum* AEPT TEAM In this work, a large-area capacitively coupled multi-frequency plasma chamber (electrode diameter: 500 mm; gap: 35 mm) is used to investigate its capability for a better control of plasma processing in the industry. The basic idea is to use the electrical asymmetry effect (EAE) by varying the phase shift between the two lower frequencies (13.56 and 27.12 MHz) in order to control the ion energy onto the grounded substrate electrode without any effect on the high ion flux generated by 60 MHz. The ion flux and the ion energies onto the grounded substrate are measured with a retarding field analyzer. By measuring the voltage signal and using a 1D-model [1] to describe the EAE, a symmetry parameter much lower than 1 was found, which reveals a very geometrically asymmetric plasma condition. Hence the range of ion energy variation by changing the phase is much lower than it needs to be to generate remarkably changes in the film properties. Further investigations have exhibited a parasitic capacitive coupling between the powered electrode and the grounded shield that surrounds the powered electrode. In conclusion, advanced experiments to confine the plasma between both electrodes were conducted that lead to a broader ion energy variation.

*The MFCCP is a sub-project of the collaborative research centre SFB-TR 87 funded by the German Research Foundation. We want to thank Douglas Keil from LAM Research for sharing his experiences with us.

[1]E. Schüngel *et al.*, Plasma Proc. Polym. **14**, 1600117 (2017).

GT1 25 The effect of pressure and driving frequency on electron heating in a capacitively coupled oxygen discharge JON TOMAS GUDMUNDSSON, *University of Iceland, Reykjavik, Iceland and Department of Space and Plasma Physics, KTH–Royal Institute of Technology, Stockholm, Sweden* DAVID I. SNORRASON, HOLMFRIDUR HANNESDOTTIR, *University of Iceland, Reykjavik, Iceland* We use the one-dimensional object-oriented particle-in-cell Monte Carlo collision code oopd1 to study the evolution of the charged particle density profiles, electron heating mechanism, and the electron energy probability function (EEPF) in a capacitively coupled oxygen discharge with pressure and driving frequency. We find that at higher pressure (50–500 mTorr) the electron heating occurs mainly in the sheath region, and detachment by the metastable singlet molecules significant has a significant influence. At a low pressure (10 mTorr) and driving frequency of 13.56 MHz, Ohmic heating in the bulk plasma (the electronegative core) dominates. However, as the driving frequency is increased the electron heating transitions to occur mainly in the sheath region. Thus at low pressure and low driving frequency, the EEPF is convex and as the driving frequency is increased the number of low energy electrons increases and the number of higher energy electrons (>10 eV) decreases, and the EEPF develops a concave shape or becomes bi-Maxwellian. Furthermore, we find that adding detachment by the metastable states can significantly influence the peak of the ion energy distribution for O_2^+-ions bombarding the powered electrode, and hence the average ion energy and ion flux.

GT1 26 Two-dimensional fluid simulation in a radio frequency capacitively coupled plasma sustained in $SiH_4/N_2/O_2$* WENZHU JIA, YUANHONG SONG, YOUNIAN WANG, *Dalian University of Technology* In a low pressure radio frequency capacitively coupled plasma sustained in $SiH_4/N_2/O_2$ gas mixture, we investigate how the dielectric layer on the bottom electrode plays it's role on the plasma characteristics by using a two-dimensional fluid model. The simulation results show that the presence of the dielectric layer could effectively suppress the non-uniformity of plasma caused by the edge effect. When the dielectric thickness increases to a certain value, the discharge will be extinguished. In addition, for the possible gas-phase precursors in $SiH_4/N_2/O_2$ gas mixture, nitrogen, silicon, and oxygen-containing species are examined as a function of the pressure and composition ratio of the mixed gas. The results show that SiH_3O, SiH_2O, O, N and NO may be the most important deposition precursors, rather than SiN and HSiNH,etc. Moreover, the large amounts of water are formed by a number of oxygen and hydrogen-containing species presented in this gas mixture. At last, the calculated deposition rate of O, N and Si atoms are also discussed in terms of the gas pressure and composition ratio in order to predict what kind of silicon-based film can be formed.

*This work was supported by the National Natural Science Foundation of China (Grant Nos. 11275038 and 11675036).

GT1 27 Experimental investigation of standing wave effect in dual-frequency capacitively coupled argon discharges: role of low frequency source* YONG-XIN LIU, KAI ZHAO, YOU-NIAN WANG, *School of Physics and Optoelectronic Technology, Dalian University of Technology, China* It is well known that the plasma non-uniformity caused by the standing wave effect has brought about great challenges for industrial applications. To improve the

TUESDAY AFTERNOON \ GT1

plasma uniformity, another low-frequency (LF) source was introduced, aiming to examine its effect on the radial distribution of plasma density in capacitively coupled argon plasma driven by a very-high-frequency (VHF, 100 MHz) source. The radial profiles of plasma density and spatio-temporal distributions of the electron-impact excitation rate were determined by utilizing a hairpin probe and the phase resolved optical emission spectroscopy, respectively. In this work, two typical cases [i.e., the LF and VHF sources are applied on one electrode (case I) and different electrodes (case II)] have been taken into account. Our experimental results indicate that for case I an excellent plasma uniformity can be achieved by adjusting the LF voltage amplitude or LF frequency, while the LF component was found to have a small effect on the plasma uniformity for case II. To understand the different results between these two cases, the electron excitation dynamic and the frequency coupling mechanism on each case were analyzed based on the measured spatio-temporal distributions of the electronic excitation rate.

*This work has been supported by the National Natural Science Foundation of China (NSFC) (Grant Nos. 11335004 and 11405018).

GT1 28 Simulation of a pulse-modulated radio-frequency atmospheric pressure glow discharge in Argon-Oxygen mixture* XUECHUN LI, HUI LIU, YOUNIAN WANG, *Dalian University of Technology* The pulse-modulate radio-frequency atmospheric pressure glow discharges (RF- APGDs) plasmas can achieve low temperature RF APGDs with reduced power consumption. As a new discharge form, it has been investigated for applications in trials in cancer therapy, sterilization, air pollution control, etc. And it has been confirmed that ROS(Reactive oxygen species) play a key role in the processes. Thus, the characteristics of the ROS versus various discharge parameters may be a guidance for the industrial application. In this work, we use a fluid model to simulate the plasma characteristics for pulse-modulate RF-APGDs in argon-oxygen mixture. The influences of the duty cycle of pulse-modulated on the characteristics of discharge are studied. The evolution of electron density, electron energy and various reactive species versus oxygen admixture is discussed.

*Work supported by the National Natural Science Foundation of China (No. 11175034).

GT1 29 Picosecond spectroscopy and electric field of interacting streamers on dielectric surface* TOMAS HODER, PETR SYNEK, MIRKO CERNAK, *Masaryk University, Brno, Czech Republic* Surface streamers in coplanar barrier discharge in synthetic air at 30 kPa pressure were studied by time-correlated single photon counting enhanced optical emission spectroscopy and far-field microscopy enhanced intensified CCD camera. The discharge operated in a regime where two subsequent micro-discharges appeared within the same voltage half-period. During the second micro-discharge the positive surface streamers mostly follow the interface between the area of deposited charge from the previous one and the area of uncharged dielectric surface. A suppressed streamer propagating over the area of deposited surface charge was tracked and an evidence of surface streamer reconnection is hypothesized. A spatiotemporal distribution (resolution of 120 ps and 100 microns) of the reduced electric field strength was obtained for both micro-discharges from the recorded luminosities of the molecular nitrogen. The reduced electric field of positive streamers in the first micro-discharge reached 1200 Td. For the second one, the electric field values for the streamer at the interface are slightly lower than that, while for the suppressed streamers are even higher.

*This research was funded by the Czech Science Foundation project 16-09721Y and project LO1411 (NPU I) of Ministry of Education Youth and Sports of Czech Republic.

GT1 30 Ignition voltage of atmospheric-pressure dielectric barrier discharges in argon with admixtures of HMDSO and TMS* D. LOFFHAGEN, M. M. BECKER, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* J. PHILIPP, A. K. CZERNY, C.-P. KLAGES, *TU Braunschweig, Institute for Surface Technology, Bienroder Weg 54, 38108 Braunschweig, Germany* Hexamethyldisiloxane (HMDSO) and tetramethylsilane (TMS) are frequently used as monomers in dielectric barrier discharges (DBD) for the deposition of silicon-organic films. Already small admixtures of few ppm of these monomers to the carrier gas lead to drastic changes of the discharge characteristics due to Penning ionization processes. In the present contribution, the impact of HMDSO and TMS on the ignition behavior of an atmospheric-pressure DBD in argon is analyzed experimentally and by means of numerical modeling. Rate coefficients for Penning ionization and quenching due to collisions of excited argon atoms with HMDSO and TMS, respectively, are specified by an experimental validation of results of a time-dependent, spatially one-dimensional fluid model. The experimentally observed decrease of the ignition voltage with increasing monomer admixture in the range from 0 to 200 ppm by about 60% can be reproduced with very good agreement by the validated model.

*The work was supported by the German Research Foundation under Grants LO 623/3-1 and KL 1096/23-1 and within the SFB-TRR 24.

GT1 31 Thermal and energetic study of nanosecond sparks for application to plasma-assisted combustion* NICOLAS MINESI, SERGEY STEPANYAN, ERWAN PANNIER, GABI-DANIEL STANCU, CHRISTOPHE LAUX, *EM2C Laboratory, CNRS UPR288, CentraleSupélec* Nanosecond Repetitively Pulsed (NRP) discharges are widely used for ignition and stabilization of lean combustible mixtures because of their interesting chemical, thermal and hydrodynamic effects. While the chemical and thermal effects have been extensively studied, the hydrodynamic effects have received much less attention. Yet, they provide a unique means to increase the combustion velocity by redistributing active species and heat over a large volume of gas. The aim of the present work is to understand the mechanism of hydrodynamic coupling in NRP discharges in order to maximize its effects. Parametric studies were performed in atmospheric pressure air with electrodes in pin-to-pin geometry. Time-resolved Schlieren diagnostics, optical emission spectroscopy (OES), and electrical measurements at different frequencies (0-100 kHz) have been conducted to study the dependence of the hydrodynamic effects on the energy deposited per pulse, the inter-electrode space, and the pulse repetition frequency, both in quiescent and flowing air. The potential of these discharges for combustion of lean mixtures or flow control will be discussed.

*This work has been supported by the ANR FAMAC project (ANR-12-VPTT-0002).

GT1 32 Effect of accumulated charges desorption in atmospheric pressure oxygen dielectric barrier discharge HARUAKI AKASHI, TOMOKAZU YOSHINAGA, *National Defense Academy, Japan* Recently, atmospheric dielectric barrier discharges

(DBDs) are widely applied to various fields, such as ozone generation, bio-medical field and so on. But less attentions on the mechanisms of accumulated charges behaviors between discharge space and dielectric surfaces. Golubovskii *et al.* [1], simulated Atmospheric Pressure Townsend Discharges using one dimensional fluid model with considering the effect of the charge detachments. Recently, Itoh *et al.* [2] also mentioned about desorption from dielectrics in DBDs. In the present paper, simulation with considering accumulated charges desorption by the electric field has been done using two dimensional fluid model [3]. The effect of electron desorption from the dielectrics affect significantly on the electron density distributions in the vicinity of the dielectrics. In the bulk region, less effect on the electron density distributions can be seen. And the charges accumulated on the dielectrics increase in positive on both dielectrics. As a result, the assumed condition of desorption would be inappropriate.

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[3]G. Takahashi and H. Akashi, IEEE Trans. **PS-39**, 11, 234 (2011).

GT1 33 Investigation of Discharge Processes in a High-Pressure Pulsed Arc Discharge Environment for Model Verification RICKY TANG, ANDREW FIERRO, EDWARD BARNAT, MATTHEW HOPKINS, *Sandia National Laboratories* Characteristics of a plasma generated in an arc discharge are investigated. In a discharge, various processes contribute to overall characteristics. Electron chemistry and photonic processes each play a role in establishing the discharge environment based on background pressure and gas species involved. Photonic processes have been incorporated into a PIC-DSMC plasma modeling code, showing effects of including these processes on the discharge current and generating simulated photo-emission spectra. A high-pressure arc discharge experiment was set up to validate model prediction and attempt to elucidate mechanisms of charged species interaction during discharge and in the post-arc environment. Photodetectors and optical emission spectroscopy are used to probe the plasmas and characterize their spectral responses. Discharges generated with inert and reactive gases (nitrogen and air) are studied. Furthermore, differentially-charged species in the post-arc environment interact via local electric field, resulting in current flow. Model can simulate/isolate various processes, and discharge behavior can be inferred by measuring dI/dt and compared with predicted observables, showing FFT components associated with this localized current flow due to charged species interaction.

GT1 34 Equilibrium plasma formation in coaxial plasma accelerators VIVEK SUBRAMANIAM, LAXMINARAYAN RAJA, *The University of Texas at Austin* Coaxial plasma accelerators are electromagnetic acceleration devices that utilize the Lorentz force generated by self-induced magnetic fields to accelerate high density thermal plasmas to large velocities (10Km/s). The deflagration mode of accelerator operation is achieved by introducing a neutral gas puff into an evacuated coaxial inter-electrode volume that is stood off to a high potential (5 kV). The neutral gas breaks down to form a two-temperature non-equilibrium plasma that rapidly thermalizes to produce an arc. In this work, a computational model based on the self-consistent, multi-species continuum description of the plasma is used to study the neutral gas breakdown and the incipient stages of the thermalization process. The non-equilibrium plasma model is used to obtain a timescale associated with the temperature equilibration process. The plasma model is subsequently coupled with a Navier-Stokes based flow model to yield an effective length over which the plasma equilibrates as it expands into the initially evacuated inter-electrode volume. The objective of this study is to self-consistently obtain an inlet temperature boundary condition and an effective accelerator length for a MHD model that is used to describe the equilibrium plasma as it accelerates under the effect of the Lorentz force.

GT1 35 Kinetic effects during the interaction between high density microplasma and electromagnetic wave* DMITRY LEVKO, LAXMINARAYAN RAJA, *The University of Texas at Austin* The interaction between a high-density microplasma and high-power electromagnetic wave is studied by one-dimensional Particle-in-Cell Monte Carlo collisions model coupled with the Maxwell's equations. We find the value of the amplitude of the wave field above which a fully ionized plasma is generated on the picosecond time scale. This fully ionized plasma is obtained only in the skin layer while the ionization degree of the plasma bulk is $\sim$20%. The simulation results show that such non-homogeneous distribution of plasma and gas density influences significantly the heating of plasma electrons and time evolution of the electron energy distribution function.

*Air Force Office of Scientific Research (AFOSR) through a Multi-University Research Initiative (MURI) Grant titled "Plasma-Based Reconfigurable Photonic Crystals and Metamaterials" with Dr. Mitat Birkan as the program manager.

GT1 36 Study of a micro hollow cathode discharge in Ar/N_2 used for boron nitride synthesis* CLAUDIA LAZZARONI, SALIMA KASRI, XAVIER AUBERT, GUILLAUME LOMBARDI, ALEXANDRE TALLAIRE, JOCELYN ACHARD, *LSPM - CNRS UPR 3407* NADER SADEGHI, *LIPHY - CNRS UMR 5588* A microplasma is generated in the 400 micron diameter micro hole of a molybdenum-alumina-molybdenum sandwich (MHCD type) at several hundreds of Torr in argon (Ar) with an admixture of nitrogen (N_2). MHCDs allow high electron densities and therefore we expect to reach high dissociation degree of nitrogen which is particularly suited for nitride deposition given the high bond energy of molecular nitrogen. A global model of the discharge, that combines the particle and the energy balance equations, is presented. The model is run until the steady state is reached and we obtain the plasma parameters that are the species densities and the electron temperature. A particular focus is given to the electron density and the atomic nitrogen density, a key parameter for the deposition and growth of nitride films. The model predictions are compared to experiments performed during the normal regime, when the plasma is not only confined in the hole but also expands on the cathode backside. Emission spectroscopy is used to infer the electronic density in the micro-hole via the Stark broadening of the H_β line. A parametric study is done varying the current, the gas pressure and the N_2 fraction in Ar.

*Grant ANR-16-CE08-0004 JCJC.

GT1 37 Modelling of an RF plasma jet at atmospheric pressure using complementary approaches* FLORIAN SIGENEGER, JAN SCHÄFER, RÜDIGER FOEST, DETLEF LOFFHAGEN, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* Different model approaches have been used to investigate various aspects of a non-thermal RF plasma jet operating in argon at atmospheric pressure. The jet consists of two concentric capillaries and two cylindrical electrodes driven by an RF voltage at 27.12 MHz. The studies concern the generation of a filamentary plasma

TUESDAY AFTERNOON \ GT1

in the active volume investigated by a phase-resolved single filament model and the interaction of the plasma with the gas flow and with precursor molecules additionally injected for the deposition of thin films. The latter is studied by a period-averaged axially symmetric model of the plasma jet including the effluent which is directed to a substrate. Further studies refer to the phenomena of self-organization observed e.g. in the regular azimuthal rotation of filaments. The relation between the inclination of the filaments and the azimuthal gas velocity component has been revealed by a three-dimensional hydrodynamic model of gas flow and heating using the heating profile from the the single filament model.

*The work has been partly supported by the German Research Foundation (DFG) within SFB TRR 24.

GT1 38 Nonlinear Hydrodynamic Effects in Dense Microplasmas* DYLAN PEDERSON, KONSTANTINOS KOURTZANIDIS, LAXMINARAYAN RAJA, *The University of Texas at Austin* Nonlinear behavior in plasma interactions with GHz electromagnetic waves arises from nonlinearities in the electron momentum equation, among other sources. In systems where there may be a high local electric field amplification (resonators), dense microplasmas of size much smaller than the wavelength are formed near regions of high fields. In a typical Finite-Difference Time-Domain simulation, a plasma is modeled as a (linear) Drude material, which does not capture the nonlinear polarization terms of a plasma. In this work we couple the nonlinear electron momentum equation to electromagnetic simulation in order to explore nonlinear behavior.

*We would like to acknowledge support from an AFOSR MURI with Dr. Mitat Birkan as program manager.

GT1 39 Numerical modeling of microwave driven surface discharge induced by resonantly exciting spoof surface plasmon polariton YUNHO KIM, LAXMINARAYAN RAJA, *Univ of Texas, Austin* Spoof Surface Plasmon Polariton (SSPP) is an electromagnetic wave strongly confined near the surface of a corrugated metal surface (meta-surface) filled with dielectric materials. Strong resonances from each corrugated structure couple with one another to produce highly localized wave structures with wavelength much lesser than the incident wave. The electric field amplification of the microwave at the interface of the meta-surface is used to initiate the plasma breakdown of pure argon gas at 10 Torr. A self-consistent model for the description of plasma coupled with Maxwell's equations is used in this numerical study. By carefully choosing the dimensions of each periodic structure with the use of the dispersion relations for SSPP, a uniformly elongated argon plasma is obtained near the meta-surface where electron number density reaches around $1.0*10^{19}$ m^{-3}. It is found that the nature of SSPP strongly depends on the dimensions of the meta-surface, the dielectric permittivity, and frequency which therefore determine the plasma profile.

GT1 40 Development of a Cascade Arc Discharge for an Atmosphere-vacuum Interface SHINICHI NAMBA, YUUKI IWAMOTO, MEGUMI UEDA, TAKUMA ENDO, *Hiroshima Univ.* NAOKI TAMURA, *National Institute for Fusion Science* In order to demonstrate a high-performance plasma window as a vacuum interface, a compact and low-cost wall-stabilized arc (cascade arc) discharge apparatus has been developed. The device diameter was 120 mm, a length of 100 mm and its weight of <15 kg, which had a 3.2 mm-CeW cathode, eight intermediate electrodes, and a CuW anode to generate the plasma channel with an opening of 3 mm. Absolute pressures in the discharge and expansion sections were measured to examine the performance as the plasma window. Visible emission spectroscopy to determine the plasma parameters has been carried out as well. At Ar discharge of 50 A, the gas pressure significantly decreased from 100 kPa to 0.1 kPa between the discharge channel. Spectral analysis indicated that the plasma had an electron temperature of >1 eV and a density of 2.4×10^{16} cm^{-3} at 50 A at the anode exit. By installing a higher-power water pump and cooling tower, providing a pressure of 10 atm at a flow rate of 15 L/min, we will increase the discharge current up to 100 A to obtain much hot, dense arc plasmas.

GT1 41 Numerical modeling of non-transferred arc dc plasma torch operated with plasma and sheath gases KAILASH MEHER, GANESH RAVI, *Institute for Plasma Research* KANDASAMY RAMCHANDRAN, *Bharathiar University* This work focuses on an axisymmetric model of a non-transferred arc dc plasma torch operated in nitrogen using ANSYS/FLUENT software. The plasma torch consists of a tungsten cathode, a copper anode and an auxiliary floating electrode. Nitrogen is used as plasma generating gas as well as shroud gas. Both plasma forming gas and the shroud gas is introduced axially in the plasma torch. Electrodes of the torch are also part of the computational domain. The plasma is assumed to be an electrically conducting continuum fluid. It is further assumed that, the plasma is in local thermal equilibrium and optically thin. Effect of gravity is neglected in the simulation. Equations for the conservation of energy and charge are solved in the fluid as well as in the solid domain in a coupled approach. SIMPLE algorithm is used for solving the governing equations. Distribution of velocity, temperature and current density are obtained for several operating conditions. As a result of calculation, the current density in the plasma is evolved in a self-consistent manner. Predicted electro-thermal efficiency is compared with the experimental results.

GT1 42 Experimental and Theoretical Study of the Carbon Arc: from Plasma to Nanomaterial Synthesis* VLADISLAV VEKSELMAN, ALEXANDER KHRABRY, BRENTLEY STRATTON, IGOR KAGANOVICH, YEVGENY RAITSES, *Princeton Plasma Phys Lab* LABORATORY FOR PLASMA NANOSYHTHESIS TEAM A carbon arc for nanomaterial synthesis was comprehensively studied using spectroscopic techniques and modeled by specially modified computationally fluid dynamic (CFD) code ANSYS. The arc was operated at near atmospheric pressure of He background gas. Under these conditions, the carbon arc plasma is generated and sustained by ablation of the graphite anode. The same process generates carbon feedstock for carbon nanomaterials synthesis. We performed experimental study and CFD modeling to fully characterize plasma and carbon composition in the synthesis region that is important for understanding of synthesis of carbon nanomaterials by the arc method. This study revealed dimensions of the hot arc core and a cooler region of the arc periphery where synthesis of nanostructures occurs. Measurements and simulations show that the main component in the synthesis region is C_2, which is a key precursor for synthesis of carbon nanostructures. Measurements of the voltage drop in the arc confirms hypothesis that the enhanced ablation occur due to transition of the anode sheath from electron-repelling at low arc currents to electron-attractive at high currents.

*This work was supported by U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences (BES), Materials Sciences and Engineering Division.

GT1 43 Discharge formation in air bubbles immersed in water* GEORGE NAIDIS, NATALIA BABAEVA, DMITRY TERESHONOK, BORIS SMIRNOV, *Joint Institute for High Temperatures Russian Academy of Sciences, Izhorskaya 13, Moscow 125412* Discharges in gas bubbles immersed in liquids are perspective generators of chemically reactive species for liquid treatment [1]. Previously, ignition of streamer discharge inside spherical bubbles has been simulated [2]. Often occurring deformation of bubbles changes the electric field distribution in the bubble volume, affecting the discharge inception voltage and structure of formed streamers. In this talk, the effect of distortion of air bubbles in water on the breakdown conditions is considered. Bubbles, of a fixed volume, are approximated as ellipsoids elongated along or across the direction of electric field. Results of computational study show that the value of applied electric field required for discharge ignition depends on the bubble aspect ratio, decreasing with elongation across the field direction. Obtained streamer structures are discussed.

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[2]N. Yu. Babaeva, D. V. Tereshonok, G. V. Naidis, J. Phys. D: Appl. Phys. **48**, 355201 (2015).

GT1 44 Production of electrical discharges in acoustic cavitation bubbles K. SASAKI, *Hokkaido University* N. TAKADA, Y. HAYASHI, M. GOTO, *Nagoya University* We produced electrical discharges in acoustic cavitation bubbles with the intension of enhancing the reactivity of sonochemical processes. Acoustic cavitation bubbles were generated in a rectangular vessel which was filled with water by applying an ultrasonic power at a frequency of 27 kHz. The efficient generation of cavitation bubbles was possible with the help of a punching metal plate [1]. Glowlike discharges were observed in cavitation bubbles which were attached on the bottom surface of the cylindrical high-voltage electrode. Bright optical emission was observed in the expanding period of cavitation bubbles, while we also observed electrical discharges even in the shrinking phase. The discharge was possible until 3.7 μs before the collapse of cavitation bubbles. If lifetimes longer than 3.7 μs are expected for discharge-produced reactive species, the species composition inside the collapsed cavitation bubbles with the discharge may be different from that without the discharge. The discharge in the cavitation bubbles may be helpful to enhance the reactivity of sonochemistry processes.

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GT1 45 Formation of Metal-Composite Nanoparticles by Laser Ablation under Supercritical CO_2 MARDIANSYAH MARDIS, WAHYU DIONO, NORIHARU TAKADA, HIDEKI KANDA, MOTONOBU GOTO, *Nagoya University* Gold (Au), silver (Ag), titanium (Ti) and iron (Fe) nanoparticles were produced by pulsed laser ablation (PLA) of a metal plate in supercritical CO_2. Metal plate was placed in the center of high pressure chamber and ablated by using Nd: YAG laser with 532 nm and 1064 nm of wavelength. The experiments were performed at temperatures of 31°C-80°C and pressures of 5-15 MPa with irradiation time of 15 minutes. The generated particles were analyzed by using field emission scanning electron microscopy (FE-SEM), scanning transmission electron microscopy (STEM), transmission electron microscopy (TEM) system equipped with energy dispersive X-ray spectroscopy (EDS). The results showed that the generated particles are spherical in shape with average diameter 5-100 nm. Besides, based on EDS results, the generated particles consists of carbon, oxygen and metal which provide the evidence of reaction between metal target and solution (CO_2). Moreover, the influence of CO_2 by changing the temperatures and pressures were also studied and the possible mechanisms of particles formation are discussed. This provides useful insight for the synthesis of composite nanoparticles which can be applied in several fields, such as catalysis and photonics.

GT1 46 The impact of solution chemistry on the absorption spectra of plasma-generated solvated electrons in aqueous solutions* HERNAN E. DELGADO, PAUL RUMBACH, DAVID M. BARTELS, DAVID B. GO, *University of Notre Dame* In this work, we use a low-temperature atmospheric plasma as a cathode in an electrochemical cell to generate solvated electrons, and a total internal reflection absorption spectroscopy (TIRAS) technique to measure their optical absorbance at different wavelengths. Solvated electrons are a species of great interest because of their ability to drive a variety of chemical reactions at the plasma-liquid interface. Historically, their absorption spectrum and thermodynamic properties in aqueous solutions have been studied extensively with pulse radiolysis. However, while radiation generates solvated electrons in the bulk from the solvent molecules, solvated electrons from plasma-liquid interactions form near the interface, which can lead to different behavior. For example, we have observed significant differences in the plasma-generated $(e^-)_{aq}$ optical absorption spectrum, including a shift of the spectrum toward the blue and a suppression of the Lorentzian tail on the high-energy side. We will present further study of these spectra in different solutions with varying salt (sodium perchlorate) concentrations in order to understand the interfacial behavior of plasma-solvated electrons.

*This work was supported by the US Army Research Office under Award Number W911NF-17-1-0119.

GT1 47 Resonance induced striations in electronegative capacitively coupled radio-frequency plasmas* EDMUND SCHUENGEL, *Evatec AG, Switzerland* YONG-XIN LIU, *School of Physics and Optoelectronic Technology, Dalian University of Technology, China* IHOR KOROLOV, ZOLTAN DONKO, *Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, Budapest, Hungary* JULIAN SCHULZE, *Institute for Electrical Engineering, Ruhr-University Bochum, Germany* YOU-NIAN WANG, *School of Physics and Optoelectronic Technology, Dalian University of Technology, China* The eigenfrequency of capacitively coupled radio-frequency plasmas in electronegative gases may locally match the frequency of the applied voltage. Such a resonance leads to a spatial modulation of the electric field, the densities of positive and negative ions, the energy gain of electrons, and the optical emission intensity in the plasma bulk region. Accordingly, self-organized striation patterns emerge. We investigate these striations and the physical mechanisms behind them in capacitive discharges in CF_4 by a combination of Phase Resolved Optical Emission Spectroscopy measurements and outcomes of PIC/MCC simulations for various neutral gas pressures, electrode gaps, and applied voltage frequencies and amplitudes. The distance between the striations is found to decrease as a function of pressure. Furthermore, the discharge modes and mode transitions depending on the global control parameters are mapped in a phase diagram.

*Work supported by the US NSF Grant 1601080, by the German DFG SFB TR 87, and Hungarian K-119357 and PD-121033 Grants.

GT1 48 Forming of long nanosecond pulses with the rectangular envelope in a compact active microwave pulse compressor* VLADISLAV IGUMNOV, STANISLAV GOREV, SERGEY ARTEMENKO, *National Research Tomsk Polytechnic University* The paper presents the results of research of a compact, compared to the length of the emitted wave train, active microwave compression systems. This system allow for generating high power microwave pulses with the duration from ~10 ns to ~100 ns and a rectangular pulse shape. The variant of the compression system is based on an oversized cylindrical cavity, which generates TE0 mn (m, n > 1) type oscillations and is composed of a set of (m-1) circular waveguide sections. The sections are embedded coaxially into the cavity volume. The sections have the same diameter as that of the boundaries of radial variant of working mode oscillation and also have a length of half wave less than the working wavelength of the cavity. They fixed at the input and output of the end of the cavity wall. Thus, a set of waveguide sections forms a slow-wave structure, which increased travel time of wave into the volume of a cavity. The energy output device for the cavity is designed as an interference microwave switch based on the H-tee. It was shown experimentally that such compressors form nearly rectangular shaped microwave pulses. The power of the output pulse is comparable to the power of the waves in the classical microwave compression systems.

*The work was founded by the program for improving the competitiveness of Tomsk Polytechnic University.

GT1 49 Construction of a multidipole cylindrical chamber, MAXIMUS, with magnetic X-point configuration and investigation of its plasma properties YEGEON LIM, DAEHO KWON, WON JUN LEE, *Department of Nuclear and Quantum Engineering, KAIST, Daejeon 34141, South Korea* BO SUNG KIM, *I.T.S, Daejeon 34024, South Korea* YOUNG-CHUL GHIM, *Department of Nuclear and Quantum Engineering, KAIST, Daejeon 34141, South Korea* We have constructed a low temperature DC plasma source with a cylindrical (60 cm radial and 200 cm axial) multidipole chamber, 'MAgnetic X-point sIMUlator System (MAXIMUS)', whose base pressure is $\sim 10^{-6}$ Torr. DC plasmas are generated by a number of hot tungsten filaments which can be biased up to -200 V with respect to the grounded chamber. By applying approximately 50 A of current to the filaments, we obtain plasma density of the order of 10^9 cm^{-3} with the electron temperature of ~1 eV measured by a single Langmuir probe. A set of axial copper tube through the chamber creates an axially homogeneous magnetic X-point. This configuration allows us to investigate effects of X-point to the surrounding plasmas. In this work, we present basic properties of plasmas in MAXIMUS and how we can control them.

GT1 50 Influence of Initial Conditions On Discharge-Pumped XUV Laser Beam* JIRI SCHMIDT, KAREL KOLACEK, JAROSLAV STRAUS, OLEKSANDR FROLOV, *Institute of Plasma Physics of the CAS* This work reports on recent results of the experimental device CAPEX working as an XUV laser source that is pumped by a fast capillary discharge. On this device we observed lasing at 46.9 nm (Ne-like Ar line). The initial conditions (such as pre-pulse current amplitude and duration, filling argon pressure in the capillary) play a key role on the laser beam characteristics (e.g. on the laser beam profile, and on the laser pulse energy). The external pre-pulse driver operates independently on the main capillary current. The pre-pulse current amplitude can be varied in the range from 5 A up to hundreds of A, and its duration (the pre-pulse beginning to the main current onset) can be adjusted from 3 ?s up to hundreds of ?s. We have found a significant influence of these initial conditions on the laser beam profile and on the laser pulse energy. Of course, the initial pressure of argon inside the capillary has a substantial effect on the laser beam as well. These measurements have been performed for three groups of the main capillary current amplitudes (~12 kA, ~19 kA, ~26 kA). In summary, this paper gives a systematic survey of laser beam profiles and laser pulse energies in dependence on capillary-discharge initial conditions varying in much broader ranges than ever before.

*This work was performed under auspices and with the support of the Ministry of Education, Youth, and Sports of the Czech Republic (INGO contract LG15013).

GT1 51 Characterization of a Flow-Through Low Temperature RF Plasma Reactor for Nanomaterial Synthesis NECIP UNER, ELIJAH THIMSEN, *Washington Univ* Flow-through low temperature plasmas are being increasingly studied in the laboratory, especially for producing nanomaterials. Low temperature radio frequency (RF) plasmas have been very successful for synthesizing crystalline and monodisperse semiconductor nanocrystals. Although used by many groups worldwide, thorough characterization of the reactor itself is largely missing from the literature. The flow-through reactor used in this study was a simple and easy-to-build capacitively coupled RF design comprised of a glass tube with two ring electrodes wrapped outside of the tube. Using a Langmuir double probe, electron temperature and ion density were measured as a function of axial position, input RF power, and pressure. Neutral gas temperatures were determined using a fluorescence decay temperature probe. The reactor was found to have a distinct distribution of ion density and gas temperature along its central axis. Gas temperatures were found to be significantly higher than room temperature at moderate applied RF powers. Along with a complete set of plasma parameters as a function of axial position, calculated nanoparticle temperature histories and the energy efficiency of the reactor will also be presented.

GT1 52 Neutral Flow Coupling in Helicon Plasmas EARL SCIME, ZACHARY SHORT, MIGUEL HENRIZQUEZ, JACOB MCLAUGHLIN, LUKE NEAL, DEREK THOMPSON, *West Virginia Univ* Neutral particle distributions are critical to the study of plasma boundary interactions, where ion-neutral collisions, e.g. via charge exchange, may modify energetic particle populations impacting the boundary surface. Neutral particle behavior at absorbing boundaries thus underlies a number of important plasma physics issues, such as wall loading in fusion devices and anomalous erosion in Hall thruster channels. Neutral velocity distribution functions (NVDFs) are often measured using laser-induced fluorescence (LIF). Our standard LIF scheme excites the 1s4 non-metastable state of neutral argon with 667.913 nm photons from a tunable diode laser. The subsequent decay emission at 750.590 nm is recorded synchronously with injection laser frequency. The signal-to-noise of this LIF scheme is poor. Here we present NVDF measurements using a recently developed scheme for neutral argon LIF at 706.92 nm (exciting from the 1s5 to the 2p3 state). Emission is observed at 738.60 nm (from the 2p3 state to the 1s4 state). The light source for this LIF scheme is a high-power, tunable dye laser. The NVDF measurements are compared to three-dimensional ion flow field measurements performed at the same locations in a helicon plasma source.

GT1 53 Laser Induced Fluorescence for Singly Ionized Atomic Iodine THOMAS STEINBERGER, EARL SCIME, *West Virginia University* While xenon is the standard propellant for a wide range of plasma thrusters, xenon is expensive and xenon propellant systems require heavy compressed gas tanks, pressure regulators, and other bulky hardware. Iodine has similar mass and is much easier to acquire than xenon. Iodine's natural state of matter at room temperature is solid and is easily sublimated to gas with a simple heating element. This advantage for iodine is also a significant challenge when developing gas handling systems for iodine. Another challenge for iodine thrusters is a lack of well-defined spectroscopic diagnostics for single ionized iodine, specifically, a lack of a demonstrated laser induced fluorescence (LIF) scheme. We present emission spectroscopy measurements of iodine ion emission from the $6p^5P_3 - 5d^5D_4^o$ transition at 695.878 nm and the $6p^5P_3 - 6s^5S_2^o$ transition at 516.12 nm as a function of pressure and microwave power for a microwave excited iodine plasma in a sealed quartz cell at a pressure of 1 mTorr. The $5d^5D_4^o$ state is metastable and was identified by [1] as a strong candidate for an iodine ion LIF scheme. We will also present preliminary LIF measurements using a tunable dye laser operating at 695.878 nm and new chamber design.

[1]Hargus *et al.*, 48th AIAA Joint Propulsion (2012).

GT1 54 Non-invasive plasma diagnostics using oxygen optical emissions* JOHN BOFFARD, NATHANIEL LY, CHUN C. LIN, AMY WENDT, *University of Wisconsin - Madison* The optimization and control of technological plasmas is facilitated by measurements of plasma properties. Non-invasive diagnostics based on optical emission spectroscopy (OES) rely on the prediction of recorded spectral features, using an emission model accounting for processes related to the excitation and de-excitation of photon-emitting species. Here we implement an emission model for low-pressure oxygen plasmas. We have measured the emission spectra of low pressure oxygen inductively coupled plasmas in the 350-900 nm wavelength range, yielding both atomic O lines and a few O_2^+ molecular ion bands. The model takes the intensities as inputs, returning values of dissociation fraction, and electron density and temperature, which we benchmark against O_2/Ar actinometry and Langmuir probe measurements, respectively. Trends (pressure: 1-30 mTorr, RF power: 100-2000 W) reveal that the O_2^+ emissions have a complicated dependence on the electron density. The dominant excitation mechanism shifts from simultaneous ionization-excitation of O_2 molecules at very low plasma densities to excitation of ground state O_2^+ ions at higher densities, for which it is also found that electron-induced quenching suppresses emissions from long-lived radiative levels.

*Supported by NSF Grants PHY-1617602 and PHY-1068670.

GT1 55 Noninvasive measurement of plasma parameters via the reactor substrates JI-HWAN PARK, CHIN-WOOK CHUNG, *Hanyang University* Noninvasive electrical plasma monitoring method is proposed. When a small sinusoidal voltage is applied between a bias electrode and a grounded substrate in an inductively coupled plasma reactor, the current flows through a closed circuit via the plasma. This current consists of the harmonic components due to the nonlinearity of the sheath. The plasma density and electron temperature can be obtained by using double probe harmonic current analysis. Because this method uses existing reactor substrates, noninvasive electrical measurement is possible without probe insertion. The measurement principle, experimental results, and the comparative analysis with a conventional electrical method are presented.

GT1 56 Plasma diagnostic method by using charged capacitor voltage MOO-YOUNG LEE, *Department of Nanoscale Semiconductor Engineering, Hanyang University* KYUNG-HYUN KIM, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* New plasma diagnostic method based on measuring charged capacitor voltage is proposed to obtain plasma density and electron temperature. When two square voltages which have different amplitudes are applied to a probe tip, the voltages of a capacitor connected to the probe vary due to current flowing through probe sheath. To obtain relations with plasma parameters and capacitor voltage, equivalent circuit containing nonlinear sheath and capacitor is adopted. The electron temperature and plasma density were obtained from the ratio of voltage variation during the same time based on those relations. The results are well agreement with those obtained from floating harmonic method.

GT1 57 Measurement of ion energy distributions using a capillary plate with a high-aspect ratio JUN-HYEON MOON, KYUNG-HYUN KIM, KWAN-YONG KIM, CHIN-WOOK CHUNG, *Hanyang University* An energy analyzer using a capillary plate with high-aspect ratio is proposed to measure the ion energy distribution (IED). The capillary plate replaces the role of the grid of the conventional retarding field energy analyzer and has several advantages at the same time. As using the capillary plate, the electrons are repelled by electron shading effect due to the difference in mobility of ions and electrons and the measured IED at the bottom of the capillary plate will be closer to the value at the bottom of the contact hole in etch process. In our experiment, the effect of electron repelling by the capillary plate (L/D = 40) is confirmed by measured I-V characteristic curve and COMSOL simulation. The IED is measured under various discharge conditions.

GT1 58 Generation and optical diagnostics of pulse-modulated microwave plasma in high-pressure argon KENICHI INOUE, NORITAKA SAKAKIBARA, *The University of Tokyo* JAEHO KIM, *National Institute of Advanced Industrial Science and Technology* TSUYOHITO ITO, KAZUO TERASHIMA, *The University of Tokyo* High electron density plasma in high-density media provides highly reactive environments. Such plasma could be useful for developing rapid materials processing as well as synthesizing non-equilibrium materials. To achieve high-density plasma in high-pressure argon up to 1.0 MPa, we apply pulse-modulated microwave in this study. Because of the electron confinement, microwave plasma generally reaches high electron density. Pulse modulation is expected to enhance non-equilibrium properties and to provide further controllability of the processes, e.g. keeping low temperature and suppressing heat damages to materials. The pulse-modulated microwave plasmas were generated at the pressures of 0.1-1.0 MPa with the pulse frequency of 100-1000 Hz. The spatio-temporal structure of the plasmas was investigated via high-speed-camera analysis; confirming the pulse-modulated generation of plasma in 1 mm space at 0.1 MPa. Optical emission spectroscopy and near-infrared laser heterodyne interferometry were performed; indicating that the electron densities were in the order of 10^{23} m^{-3}.

GT1 59 Mobility of $Ar^{(+)}$ IN Ar/CF_4* ZELJKA NIKITOVIC, VLADIMIR STOJANOVIC, ZORAN RASPOPOVIC, ZORAN LJ. PETROVIC, *Institute of Physics, University of Belgrade, Belgrade, Serbia* In this paper we present a cross section sets for $Ar^{(+)}$ in Ar/CF_4 where existing experimentally obtained data are selected and extrapolated. Monte Carlo code is applied to accurately calculate transport coefficients in hydrodynamic regime. We discuss new data for $Ar^{(+)}$ ions in Ar/CF_4 where flux and bulk values of reduced mobility are given as a function of reduced electric field E/N (E-electric field, N-gas density).

*Results obtained in the Institute of Physics University of Belgrade under the auspices of the Ministry of Education, Science and Technology, Projects No. 171037 and 410011.

GT1 60 Striations due to Kinetic Instability in Water Containing Atmospheric Pressure Plasmas* E. KAWAMURA, M.A. LIEBERMAN, A.J. LICHTENBERG, *Univ of California - Berkeley* Narrow gap atmospheric pressure plasmas (APPs) have wide ranging energy and biomedical applications. Common feedstock gases are helium and argon with trace H2O vapor. Discharge control for applications requires stability, but kinetic particle-in-cell (PIC) simulations of rf or dc driven narrow gap (1–4 mm) helium or argon APPs with trace H2O vapor show an ionization instability resulting in striations (spatial oscillations) in the bulk plasma. These striations are due to non-local electron kinetics and would not be observed in commonly used APP fluid simulations. We develop a striation theory which agrees well with the PIC results. Discharges with lower ion mobility μ_i and higher $K_{rec}n_0$ tend to be more unstable, where K_{rec} is the electron-ion recombination rate coefficent and n_0 is the bulk plasma density. Water-containing APPs tend to form high mass positive ion clusters with high K_{rec} and are thus more likely to exhibit striations. APPs with argon rather than helium feed stock gas are more unstable due to the reduced (stabilizing) μ_i in the heavier gas. Water-containing APPs operated at a low frequency of 50 kHz introduce a new phenomenon of time-varying n_0, which leads to a time-varying instability.

*This work was supported by the Department of Energy Office of Fusion Energy Science Contract DE-SC0001939.

GT1 61 How boundary conditions affect the plasma properties in CCRF discharges?* ANBANG SUN, *Xi'an Jiaotong University* MARKUS BECKER, DETLEF LOFFHAGEN, *INP-Greifswald* PIC/MCC methods are commonly used for the simulation of CCRF discharges. Various boundary conditions (BCs) have been used to describe the interaction of particles with the electrode surfaces. However, well-founded explanations and investigations of the influence of those BCs are very rare. In the present contribution, our 1d3v PIC/MCC code is applied to analyze the quantitative impact of electron BCs on the properties of CCRF discharges. It is shown that for the lowest gas pressure considered, the secondary electron emission (SEE) coefficient and the electron reflection coefficient have a similar impact on the plasma parameters. With increasing gas pressure, the discharge switches from alpha to gamma mode and the emission of secondary electrons becomes the dominant boundary effect. At the highest pressure of 80 Pa, the SEE strongly affects the plasma parameters while the electron reflection coefficient has almost no effect.

*The work was supported by EU PlasmaShape project (no 316216), by State Key Laboratory of Electrical Insulation and Power Equipment (no EIPE17311) of Xi'an Jiaotong University and by the German Research Foundation within CRC TRR24.

GT1 62 Effect of runaway electrons on discharge breakdown in air at atmospheric pressure: simulation study* ZDENEK BONAVENTURA, *Masaryk University, Fac. Sci., Dept. Phys. Electronics, Brno, Czech Republic.* OLIVIER CHANRION, *Technical University of Denmark, National Space Institute (DTU Space), Kgs. Lyngby, Denmark* ANNE BOURDON, *LPP, CNRS, Ecole polytechnique, Palaiseau, France* TORSTEN NEUBERT, *Technical University of Denmark, National Space Institute (DTU Space), Kgs. Lyngby, Denmark* Thanks to development of both power supplies and diagnostic techniques, a number of experiments have been performed to study the discharges obtained using high voltage pulses with sub-nanosecond rise fronts. We use a 2D axisymmetric beam-bulk hybrid model, which describes cold electrons with a fluid model and high energy electrons with a particle model, to study discharge breakdown appearing in a negative point-to-plane gap submitted to very high voltage pulse. The results show the effect of high energy electrons on discharge development. While overtaking the discharge front, the high energy electrons pre-ionize the gas ahead and leave a trace of secondary seed electrons that in turn facilitate discharge propagation. Characteristics of fast electrons generated in the region of enhanced electric field ahead of the discharge propagating front are studied in detail.

*This work has been done partially within the LABEX Plas@par project and Agence Nationale de la Recherche project ANR-11-IDEX-0004-02. ZB acknowledges support from the Czech Science Foundation research project 15-04023S.

GT1 63 Plasma chemistry round robin LEANNE PITCHFORD, *Laplace, CNRS and University Toulouse III* In response to the need for a community-wide activity on the assessment of plasma chemical kinetics in commonly used gases, a round robin exercise was proposed during the discussion session on LXCat at GEC 2016. A call for participation was then circulated and 12 teams responded. Participants were asked to calculate electron temperature and species concentrations using a 0D model of their choice. It was decided to start with a one-level system and a given set of cross sections and to compare predicted densities of species and transport parameters. Results were centralized and distributed anonymously to all participants who then had the opportunity to refine their calculations. After several rounds, good, but not perfect, agreement has been obtained using either a given E/N or a given power as the parameter, and assuming either Maxwellian or non-Maxwellian electron distribution. The round robin is now beginning comparisons in N2/O2 mixtures. In collaboration with G. Colonna, CNR-Nanotec, Italy, M. Turner, Dublin City Univ., Ireland, M. Becker, D. Loffhagen, F. Sigeneger, INP Germany, F. Gordillo, A. Luque, Inst. Of Astrophysics of Andalusia, Spain, F. Iza, F. Montazersadgh, Loughborough Univ., UK, J van Dijk, W. Graef, G. Kroesen, D. Mihailova, Eindhoven Univ. of Technology, Netherlands, A. Bogaerts, S. Heijkers, Univ of Artwerp, Belguim, L. Alves, M. Castela, V. Guerra, M. Lino da Silva, L. Marques, N. Pinhao, C. Pintassilgo, A. Tejero, Univ. of Lisbon, Portugal, T. Kozak, Univ. of West Bohemia, Czech Republic, A. Derzsi, Z. Donko, P. Hartmann, K. Kutasi, Wigner Research Centre for Physics, Hungary, S. Pancheshnyi, ABB Switzerland

GT1 64 Convergence of fluid and kinetic models in the high pressure limit MILES M. TURNER, SEAN KELLY, *Dublin City University, Ireland* ANN BOURDON, *Ecole Polytechnique, France*

Kinetic models (such as particle-in-cell simulations) are usually accepted as offering an fundamentally accurate description of low-temperature plasmas, albeit at high computational cost. Fluid models are far more economical, but less accurate. A common strategy for supplying electron transport and rate constants to a fluid model is to solve a fluid energy transport equation, and use the mean energy so computed to interpolate data obtained from a solution of the Boltzmann equation, often using the two-term spherical harmonic expansion. The fluid approach and the kinetic approach should then converge at sufficiently high pressure, where the local field approximation applies. In this work we compare the fluid and kinetic approaches for a capacitively-coupled discharge in helium over a wide range of pressures. We find that a regime of convergence is difficult to find, and perhaps does not exist under conditions where a uniform glow discharge occurs experimentally. We conclude that, in this case, the uncertainty introduced by the fluid model formulation is likely comparable with the uncertainty associated with basic data. Consequently, the basic fluid model formulation is a factor limiting the predictive capability of many present plasma simulations.

GT1 65 Computational Modeling of Nb Magnetron Sputtering in an SRF Chamber using PIC-MCC* THOMAS JENKINS, JAMES MCGUGAN, SCOTT BARTLETT, SCOTT KRUGER, CHRISTINE ROARK, *Tech-X Corporation* JONATHAN SMITH, *Tech-X UK Ltd.* DAVID SMITHE, PETER STOLTZ, *Tech-X Corporation* YI XIE, *Fermilab* A 2D axisymmetric simulation model for a cylindrical, coaxial magnetron sputtering device is presented. The model was built to simulate niobium sputtering in superconducting radio frequency cavities, in tandem with an experiment being conducted at Fermi National Accelerator Laboratory. The simulation model uses Particle-in-Cell and Finite-Difference algorithms, and is performed using the VSim software [1]. The simulation is fully self-consistent and includes an external feedback circuit, secondary electron emission, sputtering emission, and background neutral gas collisions. The magnetic field is solved within the simulation. The erosion profile, deposition profile, and detailed plasma parameters are obtained.

*Funding provided in part by US DoE SBIR awards DE-SC0009501 and DE-SC0015762.

[1]C. Nieter and J. R. Cary, J. Comput. Phys. **196**, 448 (2004).

GT1 66 Development of Three-Dimensional Kinetic Codes for Modeling of a Plasma Switch ANDREW POWIS, *Princeton University* JOHAN CARLSSON, IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory* The plasma switch is a proposed alternative mechanism for performing AC to DC (or visa-versa) power conversion within a compact and robust device. Accurate three-dimensional kinetic models for the discharge are critical towards understanding the fundamental physics and improving device performance. To this end we have updated the commercially available Partice-in-Cell, Monte-Carlo-collision (PIC-MCC) code, Large Scale Plasma (LSP) [1] for applications to low-temperature (electrostatic) plasma devices such as the plasma switch. Improvements include an updated circuit model and updated collision models [2]. Furthermore we have updated the Poisson's equation solver to take advantage of state-of-the-art direct and iterative techniques. By taking advantage of massively parallel architectures, these improvements allow us to perform self-consistent kinetic simulations of large scale systems within reasonable time frames. We foresee a wide range of applications for this code beyond the plasma switch such as plasma micro-discharges and sputtering-magnetrons.

[1]D. R. Welch *et al.*, "Integrated simulation of the generation and transport of proton beams from laser-target interaction." Phys. Plasmas **13**, 063105 (2006).

[2]J. Carlsson *et al.*, "Validation and benchmarking of two particle-in-cell codes for a glow discharge." Plasma Sources Science and Technology **26**, 014003 (2016).

GT1 67 Subnanosecond breakdown development in high-voltage pulse discharge. Main mechanisms* IRINA SCHWEIGERT, ANDREY ALEXANDROV, *Khristianovich Institute of Theoretical and Applied Mechanics* PAVEL GUGIN, MAXIM LAVRUKHIN, PETR BOKHAN, DMITRY ZAKREVSKY, *A V Rzhanov Institute of Semiconductor Physics* A subnanosecond breakdown in high-voltage pulse discharge may be a key tool for superfast commutation of high power devices. The breakdown in mid-high pressure in helium was studied in experiment and in particle-in-cell Monte Carlo collision simulations. The complex kinetic model was developed, based on kinetic simulation of discharge plasma, including dynamics of electrons, ions and fast helium atoms, produced by ions scattering. Attention was paid to electron emission processes from cathode: photoemission by Doppler-shifted resonant photons, produced in excitation processes with fast atoms; electron emission by ions and fast atoms bombardment; and the secondary electron emission (SEE) by hot electrons from bulk plasma. The simulations show that the fast atoms are the main reason of emission growth at the early stage of breakdown, but at the final stage, when the voltage on plasma gap drops, the SEE is responsible for subnanosecond rate of current growth. The influence of SEE yield for three types of cathode material (titanium, SiC, and CuAlMg-alloy) was tested. By changing the pulse voltage amplitude and gas pressure, the area of existence of subnanosecond breakdown is identified.

*Authors are grateful to the Russian Foundation of Basic Research No. 17-08-00121.

GT1 68 Effect of electron energy distribution function on formation of graphene nanocrystallites during electron-irradiation-induced carbon film growth process in an ECR Plasma* WENCONG CHEN, XI ZHANG, DONGFENG DIAO, *Shenzhen University* INSTITUTE OF NANOSURFACE SCIENCE AND ENGINEERING TEAM Recently, a low-energy electron irradiation technique was developed to deposit graphene-nanocrystallites-embedded carbon (GNEC) films which manifests unique tribological, magnetic and optoelectronic properties. However, the role played by low-energy electrons in this process remains unclear. During the electron irradiation process, substrates are positively biased and electrons produced in the plasma are accelerated to irradiate the deposited GNEC films. In this work, electron energy distribution function on the substrate surface during the electron-irradiation-induced carbon film growth process in an ECR (Electron Cyclotron Resonance) plasma is measured with a retarding field energy analyzer (RFEA). The deposition temperature is probed by an infrared thermometer. A Langmuir probe is used to monitor the plasma potential and calibrate the current sensitivity of the RFEA. It is found that the size and concentration of graphene nanocrystallites strongly depend on the irradiation electron energy and the electron flux but not the temperature, which indicates that the electron excitation effect of the covalent bonds dominate the formation process of these nanocrystallites. This finding sheds light on the interaction between the plasma and carbon materials.

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GT1 69 Computational Study of RailPAc Arc-Root Jets MILES GRAY, LAXMINARAYAN RAJA, *University of Texas at Austin* A computational study was conducted on a magnetohydrodynamic plasma actuator called the rail plasma actuator (RailPAc). The actuator consists of two parallel, 6 in long, copper rails flush mounted on an insulating ceramic plate. When a current pulse (1kA) at 100V is supplied, an electrical arc is generated and driven along the rails by the Lorentz force generated from the interaction of the arc current with the self-induced magnetic field of the arc-electrode system. The motion of the arc induces flow in the surrounding air through compression and entrainment. This induced flow may be used to reattach flow over an aerodynamic surface. An equilibrium arc model is used to simulate the propagation of the RailPAc plasma and compliments previous experimental work focused on physical characterization of the arc. Particular focus is made on the complex interaction of macroscopic jet flows generated by the arc roots with the plasma column which has been shown in the past to be critical to reliable operation of the RailPAc actuator. Implications of these interactions on actuation efficacy and actuator design are discussed.

GT1 70 Non-linear response of Hall thruster plasma to modulation of the discharge voltage* YEVGENY RAITSES, IVAN ROMADANOV, *Princeton Plasma Phys Lab* ANDREI SMOLYAKOV, *University of Saskatchewan, Canada* For cylindrical Hall thrusters, naturally occurred breathing oscillations have a characteristic frequency of ~13 kHz. The external modulation of the anode potential was applied to make this mode coherent. To determine the driving frequency, a set of natural frequencies was defined from the Fourier transform of the discharge current and the ion current in the plume. By varying driving frequency in the range of 5-20 kHz and monitoring the power spectra of the currents, we found that the coupling of the driving frequency to the intrinsic breathing mode is at frequency of this mode ~13 kHz rather than at the driving frequency. More than that, with the increase of the driving voltage, there is a non-linear response of the discharge current and the ion current as well as a shift of the breathing mode to lower frequencies. We will discuss this interesting non-linear behavior of breathing oscillations in response to driving signal.

*This work was supported by AFOSR.

GT1 71 Background pressure effects on Hall thruster discharge plasma using a full particle simulation KENTARO HARA, *Texas A&M University* SHINATORA CHO, *Japan Aerospace Exploration Agency* Facility effects play an important role when testing space propulsion devices in laboratory, which can be problematic because measurements in laboratory may significantly differ from how the device would operate in space. It has been often observed experimentally that the thruster performance, namely, specific impulse, thrust, and efficiency, increases as the background pressure in vacuum chamber increases. In this talk, we present a two-dimensional particle-in-cell simulation with Monte Carlo collision algorithm to model the discharge plasma of a Hall thruster in the presence of ingested neutral atoms from the vacuum chamber. A half-Maxwellian at room temperature is assumed for the ingested neutral atom flow. Numerical results show that ionization and acceleration regions are pushed upstream as the background pressure increases. This suggests that the distribution function of the ingested flow, i.e., non-Maxwellian distribution of the neutral atoms, affects the discharge plasma.

GT1 72 Promotion of angiogenesis using Atmospheric Pressure Plasma Derived FGF-2/VEGF* CHIHIRO KOBAYASHI, TOSHIYA YOSHIKAWA, AKIRA MORI, TAKAMICHI HIRATA, *Tokyo City University* Atmospheric pressure plasma is applied in the medical field for coagulation, sterilization, and treatment for diabetic gangrene. Direct plasma irradiation has recently been reported to promote wound healing. The aim of the present study was to clarify the mechanism by which wound healing is promoted by plasma irradiation. Therefore we focused to the nitric oxide (NO) and growth factors, which is a key component of the healing mechanism. Using an in vitro model, we investigated the effect of the atmospheric pressure plasma irradiation to mice embryonic fibroblast cell line (NIH3T3 cell) and porcine aortic endothelial cells (POAEC). We investigated expression analysis with focus on factors related to angiogenesis it was found that the transient overexpression of b-FGF and VEGF are observed after the plasma irradiation. Furthermore, in order to investigate the function of nitric oxide syntheses (NOS), we conducted an inhibition experiment using a NOS inhibitor. These data suggest that direct plasma irradiation involving ion/radical may promote endogenous NO and b-FGF/VEGF and it promotes angiogenesis activation.

*This study was supported by a Grant-in-Aid for Scientific Research on Innovative Areas (No. 24108010) from the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT).

GT1 73 Direct Near Infrared Imaging of Brain Surface Blood Vessel Using Indocyanine Green Angiography* TAKAMSA TAMURA, SAYAKA MATSUDA, SEIRA SHIGEKUNI, RISACO TANAKA, CHIHIRO TSUTSUI, TAKAMICHI HIRATA, *Graduate School of Engineering,Tokyo City Univercity* A three major disease (cancer, apoplexy, and acute myocardial infarction) becomes a serious problem in various foreign countries of the world. Especially, hypoxic-ischemic encephalopathy (HIE) caused by cardiac infarction, arrest cardiac, and suffocation, etc. is a type of brain damage that occurs when the brain doesn't receive enough oxygen and blood. From the above-mentioned background, we performed direct imaging by indocyanine green (ICG) angiography of rat's cerebral blood vessel. The contrast medium: ICG is a water-soluble, tricarbocyanine dye used in medical diagnostics. It is used for determining cardiac output, hepatic function, and liver blood flow, and for ophthalmic angiography. ICG in the blood is excited near infrared ray (NIR), generates fluorescence of 800-850 nm. The excitation of ICG used 780 nm Infrared (IR) LED array light source. Fluorescence is made an image with near-infrared (NIR) cooled CMOS camera system and long wavelength pass filter installed in the video zoom microscope. As a result, it was proven to be able to measure the behavior of the cerebral blood vessel by noncontact by using light in the near-infrared area that had the living body permeability

*This study was supported by a research Grant for strategic research of Tokyo City University.

GT1 74 Study of Atmospheric-pressure plasmas administration methods for Hypoxic-Ischemic Encephalopathy model rat* SAYAKA MATSUDA, TAKAMASA TAMURA, RISACO TANAKA, SEIRA SHIGEKUNI, CIHIRO KOBAYASHI, TAKAMICHI HIRATA, MASAYA WATADA, AKIRA MORI, *Graduate School of Engineering, Tokyo City University* In recent years, atmospheric-pressure plasmas are applied in various fields and also develop in the medical applications. Although the mechanism of action remains unclear, new biomedical applications of plasma have been found. Experiments using atmospheric pressure plasmas confirmed several effects such as burn healing with angiogenesis, the increasing of SpO2 and improvement of circulatory function. Therefore, we have been focusing treatment of Hypoxic Ischemic Encephalopathy (HIE) by using the atmospheric-pressure plasma. HIE caused by the discontinuation of blood supplied means that a part of the brain is necrotized and a brain function is impaired. Cause of HIE is various, for example, respiratory failure and circulatory failure, neonatal asphyxia. There is no fundamental therapy for HIE except for symptomatic therapy as of now. Because of preservation and recovery of brain functions can be expected by the action of plasma, as a study on HIE treatment using atmospheric-pressure plasma, we consider and report on a method of administrating atmospheric-pressure plasma to HIE model rat at first.

*This study was supported by a Grant-in-Aid for Scientific Research on Innovative Areas (No. 24108010) from the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT).

GT1 75 Evaluation of characteristics of Multi-purpose Atmospheric Pressure Plasma Device* SEIRA SHIGEKUNI, RISACO TANAKA, TAKAMASA TAMURA, SAYAKA MATSUDA, CHIHIRO KOBAYASHI, TAKAMICHI HIRATA, *Graduate School of Engineering, Tokyo City University* The atmospheric pressure plasma (APP) doesn't stop at the industrial field, and application is also developed in the medical field. But commercialization is precedent to plasma medical equipment only by empirical fact, and there're many indefinite points in a mechanism of revival in biomedical tissue. In generally, the flow of APP source includes active oxygen species (ROS) such as ozone (O_3), hydroxyl radical (OH), hydrogen peroxide (H_2O_2), nitric oxide (NO), nitrite (NO_2), and active nitrogen species (RNS), etc. generated around the plasma flow. In view of the above background, in this research, we are developing a prototype and evaluation of an atmospheric pressure plasma source for the purpose of controlling radical species. Previous experiments confirmed that it is possible to easily change the plasma product by controlling the plasma parameters. In this presentation we will report on the consideration of the power supply unit.

*This study was supported by a Grant-in-Aid for Scientific Research on Innovative Areas (No. 24108010) from the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT).

GT1 76 Healing mechanism clarification of plasma irradiated wound by quantification and detection of superoxide dismutase (SOD) activity* RISACO TANAKA, SEIRA SHIGEKUNI, SAYAKA MATSUDA, TAKAMASA TAMURA, CHIHIRO KOBAYASHI, AKIRA MORI, TAKAMICHI HIRATA, *Graduate School of Engineering, Tokyo City University* Plasma medicine is currently applied in clinical settings, in many cases, without any explanation for its mechanism. This study therefore aims to elucidate the mechanism of healing by plasma irradiation in burn injury, by focusing on plasma wound healing. In preceding studies, it has been reported that atmospheric pressure plasma generates reactive oxygen species (ROS) and that mild oxidative stress promotes cell proliferation, which suggests that oxidative stress may play a major role in the mechanism in which plasma irradiation promotes healing burn injury. Based on these, we first measured superoxide dismutase (SOD) activity, an oxidative stress marker, at burn injury sites that were artificially created on the back of rats. We now report the results of comparative investigation of differences in SOD activity in case of non-treatment and plasma irradiation. In particular, we focused on the change in SOD activity over time. From the result, it is suggested that SOD activity of *in vivo* changes in proportion to the time course.

*This study was supported by a Grant-in-Aid for Scientific Research on Innovative Areas (No. 24108010) from the Ministry of Education, Culture, Sports, Science and Technology, Japan (MEXT).

GT1 77 DNA damage and its mechanism induced by cisplatin and 10 eV electron collision* YEUNSOO PARK, YOUNG ROCK CHOI, YOUGHYUN KIM, DAE CHUL KIM, *National Fusion Research Institute* PLASMA FUNDAMENTAL TECHNOLOGY RESEARCH TEAM, PLASMA ELEMENTAL TECHNOLOGY RESEARCH TEAM Low energy electrons (LEE, especially below 10 eV) can generate strand breaks on DNA via energy resonance mechanism named dissociative electron attachment (DEA). Interestingly, this indirect damage is a considerable yield compared to direct damage by high energy quanta ionization. To better understand of LEE roles on DNA damage in plasma and radiation fields, it needs to investigate experimental and theoretical studies at the molecular level. Definitely, it needs diverse interaction data between LEEs and biomolecules to interpret damage mechanism. We have tried to investigate DNA damage induced by single and synergistic effects of cisplatin and 10 eV electron. All dried DNA samples were irradiated by 10 eV electrons under ultra-high vacuum. And then, the samples were analyzed by high-performance liquid chromatography-tandem mass spectrometry. We compared the yields of different types of DNA damage such as strand break, base release and modification. We also suggested the possible mechanisms of DNA damage originated by cisplatin bonding and LEE collision based on current experimental findings. Finally, we expect that this study can help to find out the cause of cancer or genetic diseases and a novel therapy for them.

*This work was supported by R&D Program of 'Plasma Convergence & Fundamental Research' through the National Fusion Research Institute of Korea (NFRI) funded by the Government funds.

GT1 78 Effects of atmospheric-pressure plasma irradiation on germination and growth of radish sprouts* SHINJI YOSHIMURA, HIROSHI KASAHARA, *National Institute for Fusion Science* Positive effects of atmospheric-pressure nonequilibrium plasma irradiation on plant seeds have recently been studied worldwide, and enhancement of seed germination and seedling growth has been reported by many research groups. However, there are wide varieties of the reported effects, which may be attributable to the difference of plasma parameter, plant seed species and growth environment. This study aims to investigate the effects of plasma irradiation onto plant seeds and to provide a new set of results under a controlled growth environment. We chose radish sprouts seeds (*R*aphanus sativus L.) as test plant seeds because of their short growth period and adequate amount of preceding research reports. We used two types of atmospheric pressure discharge devices (NU-Global, PN-110+TPN-20, HUMAP-WSAP-50) with helium or argon as feed gas. The plasma-treated seeds were cultivated in a plant growth chamber (incubator) with temperature and relative humidity control. Comparison of the germination and growth rate as well as the average plant length of plasma-treated seeds with those of non-treated control seeds will be presented.

*This research was supported by the Grant of Joint Research by the National Institutes of Natural Sciences (NINS).

SESSION JW1: GAS PHASE PLASMA CHEMISTRY I
Wednesday Morning, 8 November 2017
Room: Salon D at 8:00
Sergey Macheret, Purdue University, presiding

Contributed Papers

8:00
JW1 1 Global model of Negative Hydrogen Ion Source SERGEY AVERKIN, JOHN CARY, THOMAS JENKINS, SCOTT KRUGER, MADHUSUDHAN KUNDRAPU, SETH VEITZER, *Tech-X Corporation* A global model is applied to investigate complicated chemistry in a Negative Hydrogen Ion Source in preparation for the spatially varying simulations using USim, a multi-species fluid code. The global model includes electrons, neutral hydrogen molecules with all vibrational states ($H_2(v)$), hydrogen atoms in the first 3 electronic states (H(n)), and ground state ions (H^+, H_2^+, H_3^+, and H^-). The model includes a comprehensive set of surface and volume chemical reactions. In the global model, steady state species continuity equations, electron energy and total energy equations, heat transfer to walls, and quasineutrality are solved simultaneously in order to calculate number densities and temperatures of plasma components in the discharge over a wide range of parameters (pressures and absorbed powers). These simulations allow one to extract the most important species and reactions in a Negative Hydrogen Son Source.

8:15
JW1 2 Collisional radiative model for Ar/O_2 plasma with reliable fine structure resolved cross sections* PRITI PRITI, *Indian Institute of Technology Roorkee, Roorkee, India* REETESH GANGWAR, *Weizmann Institute of Science, Rehovot, Israel* RAJESH SRIVASTAVA, *Indian Institute of Technology Roorkee, Roorkee, India* A collisional radiative (CR) model has been developed for Ar/O_2 mixture plasma. Here we extend our previous CR model for pure Ar plasma [1] by including the quenching of the excited Ar atoms with O_2 along with the other processes *viz.* radiative population transfer, electron impact excitation and ionization. Since electron collision processes play vital role, a complete data set obtained using relativistic distorted wave theory is used. Present work is in the light of recent measurement [2] on Ar/O_2(0-5%) mixture plasma at 2 Torr pressure. Diagnostics have been done by optimizing the normalized intensities obtained from this model with the measured intensities [2] for different transitions between fine stricture levels. The population densities of fine structure states of Ar(1s) are obtained and compared with the measurements [2] at different O_2 fractions. The electron temperature is found to increase (0.9 to 1.8 eV) with O_2 fraction (0-5%).

*Work is supported by SERB-DST and CSIR, New Delhi.

[1]Dipti *et al.*, Eur. Phys. J. D **67**, 203 (2013).
[2]Jogi *et al.*, J. Phys. D: Appl. Phys. **47**, 335206 (2014).

8:30
JW1 3 A zero dimensional model of microwave induced coaxial surface wave discharge fed with hexamethyldisiloxane/oxygen* EFE KEMANECI, RALF PETER BRINKMANN, *Institute for Theoretical Electrical Engineering, Ruhr-University Bochum, Germany* FELIX MITSCHKER, PETER AWAKOWICZ, *Institute for Electrical Engineering and Plasma Technology, Ruhr-University Bochum, Germany* A zero-dimensional global model is developed to analyse a microwave induced coaxial discharge of examethyldisiloxane/oxygen. The wall flux is analytically estimated and the model is validated by comparing against a variety of measurements for a feeding gas of argon or oxygen. Ion wall flux significantly contributes to the net loss rate of the positive ions. A primary chemical kinetics is added to the oxygen study to investigate the characteristics of the plasma with admixture ratio of 50:100 (HMDSO/O_2). Even though the dominant background gas is oxygen, the simulations suggest that the highest positive ion concentration belongs to $Si_2OC_5H_{15}^+$ that is also confirmed by measurements. The simulation results are compared with existing measurements and an agreement is obtained.

*Deutsch Bundesministerium fur Bildung und Forschung via PluTO$^+$.

8:45
JW1 4 Vibrational excitation and temperature evolution in a pulsed CO_2 discharge OLIVIER GUAITELLA, ANA-SOFIA MORILLO-CANDAS, DAVID YAP, CYRIL DRAG, JEAN-PAUL BOOTH, *Laboratory of Plasma Physics, CNRS, Ecole Polytechnique, UPMC, Université Paris-Saclay, 91128 Palaiseau, France* BART KLARENAAR, RICHARD ENGELN, *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Nether- lands* MARIJA GROFULOVIC, TIAGO SILVA, VASCO GUERRA, *Instituto de Plasmas e Fuso Nuclear, Instituto Superior Tecnico, Universidade de Lisboa 1049-001 Lisboa, Portugal* In spite of the abundant literature on CO_2 lasers, many energy transfer coefficients are still missing to accurately describe the vibrational kinetic in CO_2 and CO_2 containing plasmas that are investigated for CO_2 recycling technologies. A set of complementary measurements is performed in a simple pulsed glow discharge in order to provide constraints to kinetic models of such plasmas. Time resolved in situ FTIR is used to obtain vibrational temperature of CO_2 and CO during plasma pulses and the afterglow. High spectral resolution TALIF gives simultaneously O atoms density and also their temperature from the Doppler broadened profile of the fluorescence line of O atoms. The time evolution of gas temperature is obtained from Raman scattering measurements. The knowledge of gas temperature, vibrational temperature, radical and molecules densities, and electric field in the same plasma cell allow exhibiting the influence of surface properties on the plasma dynamics as well as detailed comparison with kinetic modeling of the gas phase. In addition of pure CO_2 plasma, several experiments are carried out in CO_2/N_2 and CO_2/CH_4 in contact with catalytic materials for molecules synthesis purpose.

9:00
JW1 5 Selfconsistent Vibrational and Free Electron Kinetics in Reacting CO_2/CO Plasmas LUCIA DANIELA PIETANZA, GIANPIERO COLONNA, MARIO CAPITELLI, *PLASMI Lab CNR NANOTEC Bari* A self-consistent time–dependent model based on the coupling between the Boltzmann equation for free electrons, the non equilibrium vibrational kinetics for the asymmetric mode of CO_2 and for CO vibrational levels and simplified global models for the dissociation and ionization plasma chemistry is applied to conditions met under pulsed microwave, dielectric barrier discharge and nanosecond pulsed discharges. The results show that, in MW conditions, large concentrations of vibrational excited states are generated, which affect the electron energy distribution function through superelastic vibrational collisions. Moreover, in discharge and post-discharge conditions, the vibrational distribution functions of both CO_2 and CO are characterized by plateaux due to V-V up pumping mechanism. These plateaux promote dissociation processes by pure vibrational mechanisms, which can overcome the electron impact dissociation rates. The eedf in post-discharge conditions shows characteristic plateaux due to superelastic processes

involving the electronic excited states of the species of both CO_2 and CO species.

9:15

JW1 6 Reaction DB construction of Perfluorocarbons for Plasma process simulation SATOSHI NAKAMURA, REI SAKUMA, *ET Center, Samsung R&D Institute Japan* SUN-TAEK LIM, *Semiconductor R&D Center, Samsung Electronics* SHOGO SAKURAI, HIROYUKI KUBOTERA, KIYOSHI ISHIKAWA, *ET Center, Samsung R&D Institute Japan* KEUN-HO LEE, *Semiconductor R&D Center, Samsung Electronics* Plasma process simulation plays an important role for the development of plasma etching process in the semiconductor industry. Although the results of the simulation are primarily depends on DB of the cross section and/or reaction rate for the scattering between molecules and electron in the gas phase, their data are still insufficient. In this presentation, we propose a semi-empirical method to evaluate cross-sections for some perfluorocarbons which are widely employed in the plasma etching process. There are various established methods to calculate cross sections for impact dissociation via excitation process, dissociative/non-dissociative ionization, and dissociative electron attachment except for non-dissociative electron attachment (NDEA). Using specific relation between peak value and peak energy of the cross section from experimental data for NDEA of some perfluorocarbons (CF_4, C_2F_6, C_3F_8, and so on), and combined with first-principles calculations we obtained reasonable cross-sections for NDEA of molecules whose experimental data are absent. This approach will be applied for other gases and other types of reactions without NDEA to increase DB for Plasma process simulation.

SESSION JW2: DIAGNOSTICS II

Wednesday Morning, 8 November 2017
Room: Duquesne at 8:00
Terry Sheridan, Ohio Northern University, presiding

Contributed Papers

8:00

JW2 1 An Electron Density Diagnostic Based on Doppler-free Measurement of Stark Broadening* ABDULLAH ZAFAR, *North Carolina State University* ELIJAH MARTIN, *Oak Ridge National Laboratory* STEVE SHANNON, *North Carolina State University* Passive spectroscopic measurements of Stark broadening have been reliably used to determine electron density for decades. However, a low-density limit (~1013 cm^{-3}) exists due to Doppler and instrument broadening of the spectral line profile. A synthetic diagnostic for measuring electron density capable of high temporal (ms) and spatial (mm) resolution is currently under development at Oak Ridge National Laboratory. The diagnostic is based on measuring the Stark broadened, Doppler-free, spectral line profile of a Balmar series transition using a laser-based technique. The diagnostic approach outlined here greatly reduces line broadening using Doppler-free saturation spectroscopy (DFSS), allowing access to Stark broadening regimes at lower densities than previously realized. This technique has been successfully employed to measure spectral data in an electron cyclotron resonance (ECR) source for an electron density range of 1011-1012 cm-3. Theoretical modeling continue to improve as diagnostic artifacts, such as crossover peaks, are better understood and captured in the simulations. Details of diagnostic implementation and agreement between experimental data and theoretical results is discussed.

*GAANN Fellowship Program and UT-Battelle. Oak Ridge National Laboratory is managed by UT- Battelle, LLC, for the US. Department of Energy under Contract DE-AC05-00OR22725.

8:15

JW2 2 Optical Emission Diagnostics of a Non-equilibrium Helium Plasma Jet at 1 atm in Ambient Air* VINCENT M DONNELLY, TAM NGUYEN, DEMETRE J ECONOMOU, *University of Houston* We studied a He 200 kHz rf plasma jet emerging into open air from a quartz tube wrapped by a grounded and an rf-powered electrode. The jet impinged on a dielectric substrate (MgF_2 or fused silica). VUV to near IR emission spectra were recorded through the substrate either along the discharge axis, or at a steep angle to isolate emission close to the surface. Time-resolved emission was observed close to the surface only during a brief period near to just past the peak in the positive applied rf voltage. No emission was observed during the negative voltage with the exception of a weak emission from $N_2(C^3\Pi_u \rightarrow B^3\Pi_g)$ just prior to peak negative voltage. With the exception of $N_2(C^3\Pi_u)$, emissions along the discharge axis from impurities mixing into the He flow just outside the nozzle were dominated by dissociative excitation via He metastables (He*). Axial emission from N_2^+ was also produced by collisions with He* (i.e. Penning ionization of N_2). These emissions were only modulated to a small degree during the rf period, and were shifted in phase with respect to the peak positive and negative voltages, reflecting the lifetime of He*. Detailed analysis of the emission temporal dependences revealed details of discharge kinetics.

*Work funded by the Department of Energy, Office of Fusion Energy Science, Contract No. DE-SC0001319.

8:30

JW2 3 State-by-state spectra fitting tool for highly-non-equilibrium plasmas: discharge in contact with water* TOMAS HODER, JAN VORAC, PETR SYNEK, *Masaryk University, Brno, Czech Republic* Recently, the interest in discharges in contact with water increased enormously. Often, the discharges are ignited in a noble gas and the atoms and water fragments are the only available spectral signature. In such cases, the spectrum of hydroxyl radical may seem attractive for neutral gas thermometry. This contribution brings an extensive analysis of OH(A-X) spectrum obtained on special case of kHz driven surface DBD in contact with water. We have observed a spectrum that can be interpreted as a superposition of emission from several groups of OH. We have distinguished three groups - *cold group*, best observable for low *N'* quantum numbers, *hot group*, best observable for higher *N'* quantum numbers and the third group influenced by iso-energetic vibrational energetic transfer OH(A,v'=1 ->v'=0), best observable for $8 < N' < 14$. The data was processed by the novel method of state-by-state fitting. This approach combines spectral simulation and traditional Boltzmann plot construction procedure. A synthetic spectrum is simulated for each rovibronic upper state, including the instrumental broadening and matched with the measurement. This functionality was incorporated to the massiveOES software.

*This research was funded by the Czech Science Foundation project 16-09721Y and project LO1411 (NPU I) of Ministry of Education Youth and Sports of Czech Republic.

8:45

JW2 4 IEDF distortion in high voltage retarding field energy analyzers* STEVEN SHANNON, MATTHEW TALLEY, *North Carolina State University* JOHN VERBONCOEUR, *Michigan State University* LEE CHEN, *Tokyo Electron America* There is a need for

IEDF measurement at increasingly high voltages in the kV range, particularly (but not limited to) the characterization of industrial systems that rely on high energy ions to achieve desired process conditions for material removal, deposition, or modification. Field variation, surface charge accumulation, and space charge formation within an RFEA diagnostic can limit the energy resolution of the sensor and in some cases provide distorted IEDF's when typical first derivative analysis of the sensor's VI characteristic is employed. Design considerations for an RFEA capable of operation in a capacitive RF system with sheath voltages in the kV range are presented, and show how IEDF energy resolution is impacted through design considerations such as grid geometry, spacing, and between-grid channel design. Space charge induced IEDF distortion when employing VI differentiation techniques will be presented. Specifically, distortion of the low energy portion of an IEDF due to space charge effects as well as pathways for resolving this distortion phenomenon through data analysis will be presented.

*This work is supported through a generous Grant from Tokyo Electron Limited.

Invited Papers

9:00
JW2 5 Single Emission-Line-Ratio Techniques for Correlating Reduced Electric Field, Electron Energy Distribution, and Metastable-Atom Density in a Pulsed Argon Discharge
JIM FRANEK, *West Virginia University*

Argon emission lines, particularly those in the near-infrared region (700-900 nm), are used to determine plasma properties in low-temperature, partially ionized plasmas to determine effective electron temperature and argon excited state density using appropriately assumed electron energy distributions. While the effect of radiation trapping is included in the interpretation of plasma properties from emission-line ratio analysis, eliminating the need to account for these effects by directly observing the 3px-to-1sy transitions is preferable in most cases as this simplifies the analysis. The extended coronal model is used to acquire an expression for 420.1-419.8 nm emission-line ratio, which is sensitive to direct electron-impact excitation of argon excited states as well as stepwise electron-impact excitation of argon excited states for the purpose of inferring plasma quantities from experimental measurements. Initial inspection of the 420.1-419.8 nm emission-line ratio suggests the pulse may be empirically divided into three distinct stages. Using equilibrium electron energy distributions from simulation to deduce excitation rates in the extended coronal model affords agreement between predicted and observed metastable density. Applying this diagnostic technique to lower-resolution spectroscopic systems is not straightforward, however, as the 419.8 nm and 420.1 nm emission-line profiles are convolved and become insufficiently resolved for treating the convolution as two separate emission-lines. To remedy this, the argon 425.9 nm emission-line is evaluated as a proxy for the 419.8 nm emission-line as they are both attributed to direct excitation from the argon ground state. The intensity of the 425.9 nm emission-line is compared to the intensity of the 419.8 nm emission-line over a range of plasma conditions to infer the same plasma quantities from similar experimental measurements. Discrepancies between the observed intensities of the emission-lines are explained by electron-impact cross-sections of their parent states and the electron energy distribution.

SESSION JW3: ANTIMATTER AND OTHER PROCESSES
Wednesday Morning, 8 November 2017; Room: Oakmont Junior Ballroom at 8:00; James Colgan, Los Alamos National Laboratory, presiding

Invited Papers

8:00
JW3 1 Fresh Insights and Initiatives in Low Energy Scattering Processes Involving Antiparticles
MICHAEL CHARLTON, *Swansea University*

We will review aspects of the scattering of antiparticles, and in particular processes used in the controlled formation of antihydrogen atoms with low enough kinetic energies to allow their storage in magnetic minimum neutral atom traps [1–3], an advance that has led to the first determination of some of the properties of the anti-atom [4–7]. When antihydrogen is created via the mixing of dense clouds of cold positrons and antiprotons, radial transport of the antiprotons occurs due to repeated cycles of antihydrogen formation and break-up. We will describe how simulations [8] have elucidated the underlying physics, and explore some the implications for improved antihydrogen trapping efficiencies. There is renewed interest in the use of excited state positronium to form antihydrogen. We will review recent theoretical activity in this field from which accurate data for sub-eV positronium-antiproton collisions have become available for the first time [9-12]. We describe how it may be feasible to use charge exchange in collisions of positronium with ions to create a range of cold atomic species [13], including some which, to date, have not been amenable to laser cooling.

[1]G. B. Andresen *et al.* (ALPHA Collaboration), Nature **468**, 673 (2010).

[2]G. B. Andresen et al. (ALPHA Collaboration), Nat. Phys. **7**, 558 (2011).
[3]G. Gabrielse et al. (ATRAP Collaboration), Phys. Rev. Lett. **108**, 113002 (2012).
[4]M. Ahmadi et al. (ALPHA Collaboration), Nature **541**, 506 (2017).
[5]C. Amole et al. (ALPHA Collaboration), Nat. Commun. **5**, 3955 (2014).
[6]M. Ahmadi et al. (ALPHA Collaboration), Nature **529**, 373 (2016).
[7]C. Amole et al., (ALPHA Collaboration), Nature **483**, 439 (2012).
[8]S. Jonsell et al., J. Phys B: At. Mol. Opt. Phys. **49**, 134004 (2016).
[9]A. S. Kadyrov et al., Phys. Rev. Lett. **114**, 183201 (2015).
[10]C. M. Rawlins et al., Phys. Rev. A **93**, 012709 (2016).
[11]M. Charlton et al., Phys. Rev. A **94**, 032701 (2016).
[12]I. I. Fabrikant et al., J. Phys. B: At. Mol. Opt. Phys. **50**, 134001 (2017).
[13]W. A. Bertsche et al., New J. Phys. **19**, 053020 (2017).

8:30

JW3 2 Gaseous Positronics – Cross Sections, Scattering Dynamics And Applications For Low Energy Positron Interactions With Matter*

STEPHEN BUCKMAN, *Australian National University*

Intense beams of low-energy positrons with high energy resolution are now available through the use of buffer-gas (Surko) traps. These have led to measurements of interaction cross sections for a broad range of atoms and molecules, including molecules of biological interest. The increased energy resolution, and experimental techniques developed for scattering in strong magnetic fields has also enabled highly accurate measurements of discrete excitation processes such as electronic and vibrational excitation, positronium formation and ionization in a range of atomic and molecular species. This talk will review some of these measurements, including recent studies of near-threshold ionization, and discuss their application in new and sophisticated models of positron transport, with particular emphasis on potential applications in Positron Emission Tomography.

*This work is part of a broad collaboration between the ANU (James Sullivan, Joshua Machacek), Flinders University (Michael Brunger), James Cook University (Ronald White and co-workers) CSIC Madrid (Gustavo Garcia) and the Institute of Physics, Belgrade (Zoran Petrovic and colleagues).

Contributed Papers

9:00

JW3 3 State-resolved photon-H_2^+ cross sections and rate coefficients* MARK ZAMMIT, *Los Alamos National Laboratory* JEREMY SAVAGE, *Curtin University* JAMES COLGAN, *Los Alamos National Laboratory* DMITRY FURSA, *Curtin University* DAVID KILCREASE, CHRISTOPHER FONTES, PETER HAKEL, EDDY TIMMERMANS, *Los Alamos National Laboratory* Studies of molecular plasmas both in local thermodynamic equilibrium (LTE) and non-LTE require state-resolved (electronic, vibrational and rotationally resolved) transition cross sections or rate coefficients to calculate populations (for non-LTE plasmas), opacities and emissivities. Here we present state-resolved results of photodissociation and radiative association of H_2^+ and its isotopologues (D_2^+, T_2^+, HD^+, HT^+, and DT^+). We note that going beyond the commonly utilized "two-level" approximation of H_2^+ could be important in models when dealing with radiation temperatures that can access photon wavelengths around 100 nm. For example at these wavelengths, and a material temperature of 8400 K, the photodissociation cross section via the (second electronically excited) $2p\pi_u$ state is over three times larger than the photodissociation cross section via the (first electronically excited) $2p\sigma_u$ state.

*This work was supported by Los Alamos National Laboratory and Curtin University.

9:15

JW3 4 Aurora borealis' modelling in laboratory YULIIA BALKOVA, OLEKSII GIRKA, MAKSYM MYROSHNYK, BOHDAN BIDENKO, OLEKSANDR BIZYUKOV, *V. N. Karazin Kharkiv National University* Basic physical mechanisms of Aurora are explained in this work: solar wind' electrons flux interacts with Earth's magnetic field in Earth's atmosphere with pressure gradient. Minimum possible size of laboratory facility is estimated in order of few centimeters on the base of the mean free path and the gyroradius values. The laboratory modeling of Earth's magnetic field shape was realized by the copper coil inside the plexiglas sphere with the titanium coating (the thickness is 3 μm) deposited on sphere by vacuum-arc method. DC glow discharge serves as electron source and also it is carried out an experiment with additional hot cathode electron source to compare. Working gas (pure argon, oxygen, helium, hydrogen and air), pressure of working gas (0,08 · 0,22 Torr), an impact energy of electron flux (0,6 · 3 keV) and magnetic field intensity (30 · 230 Oe) were varied during experiments. The thickness of ionized layer increase with magnetic field intensity; the area of ionized layer increase with the impact energy of electrons; the radiation intensity of ionized layer increase with pressure of working gas.

SESSION KW1: THE WILL ALLIS PRIZE FOR THE STUDY OF IONIZED GASES
Wednesday Morning, 8 November 2017; Room: Salon D at 10:00; Bill Graham, Queen's University Belfast, presiding

Invited Papers

10:00
KW1 1 Will Allis Prize for the Study of Ionized Gases: Electron Collisions – Experiment, Theory, and Applications*
KLAUS BARTSCHAT, *Drake University*

Electron collisions with atoms, ions, and molecules represent one of the very early topics of quantum mechanics. In spite of the field's maturity, a number of recent developments in detector technology (e.g., the "reaction microscope" or the "magnetic-angle changer") and the rapid increase in computational resources have resulted in significant progress in the measurement, understanding, and theoretical/computational description of few-body Coulomb problems. Close collaborations between experimentalists and theorists worldwide continue to produce high-quality benchmark data, which allow for thoroughly testing and further developing a variety of theoretical approaches. As a result, it has now become possible to reliably calculate the vast amount of atomic data needed for detailed modelling of the physics and chemistry of planetary atmospheres, the interpretation of astrophysical data, optimizing the energy transport in reactive plasmas, and many other topics – including light-driven processes, in which electrons are produced by continuous or short-pulse ultra-intense lectromagnetic radiation. I will highlight some of the recent developments that have had a major impact on the field. This will be followed by showcasing examples, in which accurate electron collision data enabled applications in fields beyond traditional AMO physics. Finally, open problems and challenges for the future will be outlined.

*I am very grateful for fruitful scientific collaborations with many colleagues, and the long-term financial support by the NSF through the Theoretical AMO and Computational Physics programs, as well as supercomputer resources through TeraGrid and XSEDE.

SESSION LW1: BUSINESS MEETING
Wednesday Morning, 8 November 2017; Room: Salon D at 11:00;

11:00
LW1 1 Business Meeting

SESSION MW1: MICRODISCHARGES II
Wednesday Afternoon, 8 November 2017; Room: Salon D at 13:30; Naoki Shirai, Hokkaido University, presiding

Invited Papers

13:30
MW1 1 Field Emission and its Effect on Microdischarge Formation
DAVID B. GO, *Department of Aerospace and Mechanical Engineering; Department of Chemical and Biomolecular Engineering, University of Notre Dame, Notre Dame, IN*

The formation of plasmas and discharges at dimensions approaching 1 micrometer have held the plasma community's interest for nearly two decades as the potential for massive arrays and high electron densities hold significant promise for a wide variety of applications. It is now apparent that at these extreme dimensions, field emission can occur, and as an additional electron source, significantly alter the discharge dynamics. Much of the attention has focused on how field emission can reduce the breakdown voltage for plasma initiation and modify Paschen's curve [1], but less attention has focused on how it affects other plasma conditions. In recent work, we have sought to measure the canonical direct current (DC) current-voltage (i-V) curve from pre-breakdown conditions through breakdown and the onset of a glow discharge. Measurements with both different cathode materials and in different atmospheric-pressure environments reveal that when field emission is active, it can dramatically alter the i-V curve, showing very little voltage drop from breakdown to glow discharge conditions and a smooth transition through the partial glow regime [2]. Further, while it is typical for i-V curves to exhibit hysteresis, field emission appears to soften this effect and allow for both forward and backward ramping from pre-breakdown to glow and vice versa. This effect, which has also been observed under vacuum conditions, reflects the unique impact field emission has on plasma operation at the microscale, and opens the door for new and novel approaches to microdischarge devices.

[1] D. B. Go and A. Venkattraman, Microscale gas breakdown: ion-enhanced field emission and the modified Paschen's curve, J. Phys. D: Appl. Phys. **47**, 503001 (2014).
[2] M. A. Bilici, J. R. Haase, C. Boyle, D. B. Go, and R. M. Sankaran, Experimental evidence for the transition from a field emission-driven Townsend discharge to a self-sustained microplasma, J. Appl. Phys. **119**, 223301 (2016).

Contributed Papers

14:00

MW1 2 Power absorption of atmospheric-pressure microwave-line-plasma* HIROTAKA TOYODA, HARUKA SUZUKI, YUTO TAMURA, YOSUKE KOIKE, YOSHIKI BABA, *Nagoya University* Large-scale atmospheric pressure (AP) plasmas have been given much attention because of its high cost benefit and a variety of possibilities for industrial applications. Microwave discharge plasma using slot is attractive due to its ability of high-density and stable plasma production, and we have developed a long-scale AP microwave plasma (AP microwave line plasma: AP-MLP) source up to ~1 m in length using loop-structured waveguide and travelling wave. However, mechanism of uniform plasma production along the slot and power absorption behavior of this plasma source is still unclear. In this study, we discuss power absorption process using an electromagnetic simulation software. In the simulation, a long waveguide with a long slot along the waveguide is supposed. Plasma is assumed inside the slot as a resistive material (conductivity: <10 S/m) based on measured electron density and assumed collision frequency. Electromagnetic wave propagation along the waveguide and through the slot is simulated varying the resistivity of the plasma. The simulation showed that the power absorption decreases with increasing the electron density. Considering the power balance of the slot plasma, this result suggests that the fluctuation of the electron density at a certain position is stabilized by the power absorption property of the plasma, resulting in better uniformity of the plasma along the slot.

*Part of this work is supported by KAKENHI 16H03893.

14:15

MW1 3 Tuning of AC Sheath Thickness by Varying Plasma Excitation Frequency* ABBAS SEMNANI, SERGEY MACHERET, DIMITRIOS PEROULIS, *Purdue University* It is known that increasing the magnitude of discharge current, either DC or RF, in abnormal glow discharge regime results in shrinking of sheath layer. Since plasma sheath behaves mainly as a capacitor due to its low electron density, this property was successfully employed to make a current-controlled tunable RF capacitor [1]. On the other hand, RF sheath thickness also depends on the frequency of plasma excitation field. In this work and to prove this concept, an *LC* resonator with resonant frequency in the range of 100s of MHz was fabricated and measured. In this resonator, a gas discharge tube (GDT) ignited by a kHz-range electric field performs as a variable capacitor. By changing the frequency of the plasma excitation signal in the range of 1-1200 kHz, the measured resonant frequency of the *LC* resonator tuned in the range of 410 MHz to 300 MHz. This measurement clearly shows the possibility of achieving frequency-controlled sheath thickness in AC abnormal glow discharge regime.

*This work was supported in part by the National Science Foundation under Grant ECCS-1619547.

[1]A. Semnani *et al.*, IEEE Trans. Plasma Sci. **44**, 1396 (2016).

14:30

MW1 4 Contraction phenomena in surface wave driven plasmas in Ar: what are the real causes of contraction?* MARCO ANTONIO RIDENTI, JAYR DE AMORIM, *Technological Institute of Aeronautics (ITA)* VASCO GUERRA, *Instituto Superior Técnico (IST)* GEORGE PETROV, *United States Naval Research Laboratory (NRL)* ARNALDO DAL PINO, *Technological Institute of Aeronautics (ITA)* In this work we designed a model to describe a surface wave driven plasma in argon at atmospheric pressure. We included the detailed chemical kinetics dynamics of Ar and solved the mass conservation equations of the relevant neutral excited and charged species. The gas temperature radial profile was calculated by means of the thermal diffusion equation. The ground state density was estimated assuming the ideal gas law. The electric field radial profile was calculated directly from the numerical solution of the Maxwell's equations assuming the surface wave to be propagating in the TM_{00} mode. The problem was considered to be radially symmetrical, the axial variations were neglected and the equations were solved in an auto consistent fashion. We probed the model results considering three scenarios: (i) the electron energy distribution function (EEDF) was calculated by means of the Boltzmann equation; (ii) the EEDF was considered to be Maxwellian; (iii) the dissociative recombination was excluded from the chemical kinetics dynamics, but the non-equilibrium EEDF was preserved. From this analysis, we established that dissociative recombination is the leading mechanism in the constriction of surface wave plasmas.

*CAPES (edict CAPES/ITA n. 005/2014); Portuguese FCT, Project UID/FIS/50010/2013.

14:45

MW1 5 Continuum Simulation of Microplasmas with Prolate Spheroid Field Emitters ABHISHEK KUMAR VERMA, AYYASWAMY VENKATTRAMAN, *Department of Mechanical Engineering, University of California Merced, Merced, CA 95343, USA* In past three decades, microscale gas discharges using field emission cathodes have been very active research topics. Since the experimental observations of remarkable field emission with low applied voltage in field emission assisted (FEA) microplasmas, significant efforts have been devoted to fundamental understanding of such systems by means of kinetic and fluid simulations, though limited to one dimension model. This work aims to expand our understanding of FEA microdischarge dynamics over pre-and post-breakdown regime in complex geometries such as prolate spheroid. We performed 2D and 2D-axisymmetric simulation of direct current argon microplasma confined between a prolate spheroid tip and a planar electrode on unstructured grids. We employed fluid model with full momentum equation and simple argon chemistry for plasma simulation along with Fowler-Nordheim equation to model field emission surface. Our results show various plasma parameters with local field enhancement and their dependency on surface location and emitter height to radius aspect ratio, to provide a basis for device characterization, tip current, effective emission area etc. The simulation results are compared with existing experimental literature on Townsend and glow discharge regimes.

15:00

MW1 6 Kinetic Simulations of Argon Microwave Microplasmas ARGHAVAN ALAMATSAZ, ABHISHEK KUMAR VERMA, AYYASWAMY VENKATTRAMAN, *Univ of California - Merced* Microwave microplasmas have been an active research area in the last decade with applications in various fields such as metamaterials and material processing. Low-frequency microwave microplasmas have been studied experimentally and numerically. Most of these numerical studies utilize continuum modeling while kinetic methods such as Particle-in-cell with Monte Carlo collisions (PIC-MCC) can most accurately capture the nonlinearities in microplasma behavior in this regime. On the other hand, microwave microplasmas with higher frequencies have been less explored. In this regard, in the current study, we perform 1-D PIC-MCC simulations for argon microplasmas in microwave regime for a range of frequencies to explore the effect of frequency on plasma characteristics such as number density and required power to reach a specific number density. In a recent work, we used PIC-MCC for microwave microplasma with a 0.5GHz frequency which showed good agreement with the existing literature. In another study, a comparison between PIC-MCC and an in-house fluid model illustrated reasonable agreement. Another objective of this work would be comparing PIC-MCC and fluid model for higher frequencies in order to assess the validity of the fluid model in predicting microplasma behavior.

15:15

MW1 7 Fluid Modeling of Low Temperature Microwave Microplasmas AYYASWAMY VENKATTRAMAN, ABHISHEK KUMAR VERMA, *Department of Mechanical Engineering, University of California Merced, Merced, CA 95343, USA* Microwave excited microplasmas are of great interest not only to scientific research but also for developing applications in metamaterials, plasma medicine and industrial scale material processing methods. Recently computational modeling and simulation is found to be of immense importance for the advancement in fabrication, designing and developing applications based on microwave microplasma. This work demonstrates our recent developments on suitable computational model and tools for simulation and insights on physical mechanism of microwave microplasma. We performed 1D and 2D continuum simulation of microwave ignited argon microplasma in simple geometries of split ring resonators and microstrip linear resonators. We employed a widely applicable fluid model including full momentum equation and reasonable rate coefficients and transport parameters for high fidelity simulation in our finite volume parallel computational framework. The simulations intend to show the advantages of using microwave sources over DC and RF sources for transferring energy to electrons and dependence of characteristics of generated plasma on various parameters such as frequency and pressure. Comparison between some simulation cases and available experimental results in literature are also presented.

SESSION MW2: NON-EQUILIBRIUM KINETICS OF LOW-TEMPERATURE PLASMAS

Wednesday Afternoon, 8 November 2017
Room: Duquesne at 13:30
Igor Adamovich, The Ohio State University, presiding

Contributed Papers

13:30

MW2 1 O atom kinetics in RF CCP oxygen plasma at increased pressures* ANDREY VOLYNETS,† *Department of Physics, Lomonosov Moscow State University, Russia* DMITRY LOPAEV, OLGA PROSHINA, TATYANA RAKHIMOVA, ALEXANDER RAKHIMOV, *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Russia* MICROELECTRONICS DIVISION OF SINP TEAM In this study, the 80 MHz symmetric CCP discharge in quartz tube was used as a source of pure O_2 plasma of increased pressures (10 to 100 Torr). This research is mainly focused on the balance of O atoms that is governed by processes of O_2 dissociation and O atom loss. The use of time-resolved actinometry technique in the modulated discharge allowed experimentally determining dissociation rate constant k^{O2}_{diss} and atom loss frequency $^{O}_{loss}$. The O atom loss is connected with surface recombination at lower pressure and volume reactions at higher pressure. The variation of plasma parameters allowed varying gas temperature from 500 K up to 1800 K and this allowed to study the O atom generation and loss mechanisms in a wide range of gas conditions. The behavior of k^{O2}_{diss} at low E/N and the role of ozone in $^{O}_{loss}$ is discussed in detail.

*This research is supported by Russian Foundation for Basic Research (RFBR) Grant No. 16-52-16024.

†Additional affiliation: Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Russia.

13:45

MW2 2 Vibrational kinetics of non-equilibrium CO_2 plasma discharge in low-excitation regime* M GROFULOVIC, T SILVA, V GUERRA, *IPFN/IST, Universidade de Lisboa (Portugal)* C D PINTASSILGO, *Departamento de Engenharia Fésica, FEUP, Universidade do Porto (Portugal)* B L M KLARENAAR, R ENGELN, *Department of Applied Physics, TU/e - Eindhoven (Netherlands)* A S MORILLO-CANDAS, O GUAITELLA, *LPP, Ecole Polytechnique, UPMC, Université Paris Sud-11, CNRS - Palaiseau (France)* The main purpose of this work is to understand in detail the vibrational energy exchanges in non-equilibrium CO_2 plasmas. To that end, we develop a kinetic model that couples the electron Boltzmann equations to the rate balance equations describing the time evolution of various individual vibrational levels of $CO_2(X\ 1\Sigma+)$. We have investigated a low excitation regime, where $\nu_2^{max} = 5$, $\nu_3^{max} = 5$ and $\nu_1^{max} = 2$, resulting in 72 vibrationally excited levels. Validation of the model was done by comparing the time-dependent densities of the aforementioned states with measurements obtained by time-resolved in situ FTIR spectroscopy in a pulsed CO_2 dc discharge (at p = 5 Torr, I = 50 mA) and its afterglow. The calculated maintenance electric field during the pulse and the time-dependent populations are in excellent agreement with the measured values. Work is in progress to extend the study to the higher vibrational excitation.

*Partially supported by FCT Projects UID/FIS/50010/2013, PTDC/FIS-PLA/1420/2014 (PREMiERE) and Grant PD/BD/105884/2014 (PD-F APPLAuSE). VG and RE have been supported by LABEX Plas@par managed by the Agence Nationale de la Recherche (ANR-11-IDEX-0004-02).

Invited Papers

14:00

MW2 3 Kinetics of nanosecond discharges at high specific energy release*
SVETLANA STARIKOVSKAIA, *LPP Ecole Polytechnique*

Voltage pulses 5-10 kV in amplitude and a few tens of nanoseconds in duration are capable to produce highly nonequilibrium low temperature plasma in a wide pressure range, from 0.1 Torr to 15 bar. High electric fields, up to kTd, are typical for discharge front. Behind the front the electric field stays high, hundreds of Td, providing high densities of electronically excited states, high dissociation degree and so high efficiency of nanosecond discharge as a trigger for various chemically active systems. The fact that nanosecond discharges are uniform at low and moderate gas densities, and are naturally synchronized within 0.1 ns in time in the case of a multi-streamer configuration at high gas densities, is extremely attractive for laboratory-scale research. At specific deposited energies 0.5-1 eV/molecule high rate of energy relaxation from electronically excited molecules or so-called fast gas heating provides increase of gas temperature for thousands of

K during tens of nanoseconds; excitation degree becomes so high that the collisions of excited species with charged, other excited and dissociated species become important, changing "classical" low temperature plasma kinetics developed in the assumption of a small chemical perturbation of the system. A review of plasma parameters in nanosecond discharges, from fast ionization waves (FIWs) at low pressure to filamentary nanosecond surface dielectric barrier discharges (nSDBDs) at tens of bars will be given.

*Collaborators: N Lepikhin (LPP), S Shcherbanev (LPP), N Popov (MSU). ANR ASPEN, pPlas@Par, LIA KaPPA.

Contributed Papers

14:30

MW2 4 Influence of superelastic collisions on discharge properties: A self-consistent approach GIANPIERO COLONNA, *PLASMI Lab CNR NANOTEC Bari* A fundamental aspect in modeling a gas discharge is to determine the rate coefficients of electron-induced processes. An accurate approach is to solve the Boltzmann equation in the two-term approximation to calculate the electron energy distribution function (eedf), that, together with the cross sections, allows the calculation of the rates. To simplify the calculation, under the assumption that eedf relaxes much faster than the gas composition, the rate coefficients can be related only to the local electric field. This approach cannot consider the contribution of the superelastic collisions in affecting the eedf. In participating to the Round Robin activity for the verification of different plasma kinetic codes, strong effects of superelastic collisions on the plasma properties have been observed, when a self–consistent coupling of free electron and level kinetics has been considered, even in the simple argon discharge, including ionization/recombination and excitation/de-excitation of the metastable state. Effects of superelastic collisions are very important not only in the post-discharge conditions, but also in the presence of high electric field, considering both power density or E/N as input.

14:45

MW2 5 Interactions between thermodynamic and chemical non-equilibrium states in an arc plasma HE-PING LI, HENG GUO, JIAN CHEN, *Tsinghua University* DEPARTMENT OF ENGINEERING PHYSICS TEAM Since the power input rate is usually higher than the energy exchange rate between the subsystems of electrons and heavy particles in low temperature plasmas, the electron temperature typically exceeds that of heavy particles, which makes the plasmas deviate from local thermodynamic or even local chemical equilibrium state. It is indispensable to investigate the complicated fundamental processes in a non-equilibrium plasma system with the aid of numerical simulations so as to optimize the discharge operating parameters. In this study, a full non-equilibrium physical-mathematical model is employed to simulate the non-equilibrium transportation processes in a free-burning argon arc, which is regarded as a model system for arc plasmas. Based on the two-dimensional non-equilibrium modeling, the complex interactions between the electron and heavy-species sub-systems are investigated. The modeling results show that, on one hand, the collisions between electrons and heavy particles influence directly the energy and mass transfer processes between these two sub-systems; while on the other hand, there exists an interaction between the non-uniform spatial temperature distributions of electrons and heavy particles, which has never been reported in previous publications.

15:00

MW2 6 Plasma chemical reactor based on DBD for hydrocarbon synthesis VIKTOR MALANICHEV, VLADISLAV KHOMICH, MAXIM MALASHIN, *Institute for Electrophysics and Electric Power RAS* VLADIMIR SHMELEV, *Semenov Institute of Chemical Physics RAS* In a plasma chemical reactor, the conversion of hydrocarbons was experimentally recorded in the treatment of a mixture of methane and ethane by a barrier discharge. For the developed plasma chemical reactor, using the "ZDPlasKin" solution algorithm, a theoretical evaluation of the plasmokinetic processes occurring in the discharge was carried out. The experimental results are in good agreement with the theoretical estimate.

15:15

MW2 7 Theoretical study of scaling law for electron kinetics in field emission-driven microplasmas in the pre-breakdown regime* XI TAN, DAVID B. GO, *Department of Aerospace and Mechanical Engineering, University of Notre Dame, Notre Dame, IN 46556, USA* For microplasmas with a characteristic length less than 10 microns, field emission can be an important process that affects Townsend pre-breakdown regime. In this regime the electron kinetics fail to scale with the reduced electric field E/p (or E/N) due to some population of the electrons behaving ballistically or near-ballistically. This non-collisionality has been considered in a pseudo-analytical expression for the electron energy distribution (EED) that shows that the EED scales with three independent parameters – pd (collisionality), V (voltage drop across gap) and E/p. As a result the reaction rate coefficients also scale with these parameters. The model is validated using 1D particle-in-cell/Monte Carlo collision (PIC/MCC) simulations. The theory provides new scaling in pre-breakdown field emission-driven microplasmas, and a relatively simple model for identifying operating conditions for plasma chemical processes, encouraging new ideas for controlling plasma chemistry at microscales.

*National Science Foundation under Award No. FA9550-11-1-0020 and the Air Force Office of Scientific Research under Award No. FA9550-14-1-0041.

SESSION MW3: MODELLING OF PROPULSION AND EXB PLASMAS
Wednesday Afternoon, 8 November 2017
Room: Oakmont Junior Ballroom at 13:30
Salomon Janhunen, University of Saskatoon, presiding

Contributed Papers

13:30

MW3 1 Bidimensional particle-in-cell simulations : Impact of dielectric walls on electron drift instability in Hall effect thrusters* ANTOINE TAVANT, VIVIEN CROES, *LPP / Safran Aircraft Engines* TREVOR LAFLEUR, *LPP/ CNES* ANNE BOURDON, PASCAL CHARBERT, *LPP / CNRS* PLASMAS FROIDS TEAM Hall effect thrusters (HET) are one of the main technology used and studied for spacecraft electrical propulsion. Grid-less, they present net advantages. However, their operation characteristics are not understood yet, resulting in an increasing need for predictive models, and a better understanding of the plasma discharge complex behavior. HETs consist of an **E**×**B** discharge in an annular ceramic channel. One of the main characteristic of the thruster is its lifetime, limited by the ceramic channel eroded by the plasma. A better understanding of wall erosion is necessary, however long experiments are costly, and erosion diagnostics and measurements are difficult to perform. A bidimensional $r - \theta$ particle-in-cell simulation is therefore developed to investigate the plasma interaction with the ceramic walls. The dielectric aspect is emphasized: studies are done with metallic walls as well as dielectrics with various geometries and characteristics. Moreover impact and use of parietal capacitive probes is studied. Then secondary electron emissions are implemented to better understand the material effects.

*Safran Aircraft Engines / ANRT.

13:45

MW3 2 Structures induced by external magnetic field in discharge plasma* IRINA SCHWEIGERT, MICHAEL KEIDAR, *The George Washington University* THE GEORGE WASHINGTON UNIVERSITY TEAM Recently some methods to control the Hall effect thruster characteristics with applying the oblique magnetic field with respect to the channel walls are widely discussed. Nevertheless with increasing the inclination of the magnetic field, discharge plasma properties can essentially change. In this work, in kinetic simulations we consider the dc discharge plasma in the external oblique magnetic field at pressure, P=0.1 mTorr. Our purpose is to study the plasma structure modification with changing the electron temperature, magnetic field strength and obliqueness for the conditions similar to the Hall thruster ones. The plasma is embedded in a cylindrical chamber an confined by the magnetic field of 25-100 G. To describe the plasma in electro-magnetic field at low gas pressure we solve Boltzmann equations for the distribution functions for electrons and ions with 2D3V particle-in cell Monte Carlo collision method. The Poisson equation was solved to find the electrical potential and electrical field distributions. The periodical structure with ridges of ion and electron densities was found for larger obliqueness of magnetic field. The electron and ion ridges are shifted with respect to each other and double–layer structure appears across B-field and along the potential rise.

*The authors gratefully acknowledge FA9550-11-1-0160.

14:00

MW3 3 Student Excellence Award Finalist: Entangled effects of electron drift instability and secondary electron emissions in Hall effect thrusters: Insights from 2D PIC computations* VIVIEN CROES, ANTOINE TAVANT, *LPP / Safran Aircraft Engines* TREVOR LAFLEUR, *LPP / CNES* ANNE BOURDON, PASCAL CHABERT, *LPP / CNRS* COLD PLASMAS TEAM Since Hall effect thrusters (HETs) are one of the most successful electric propulsion (EP) technologies, the need for improved predictive models is increasing. Yet HETs complexity makes it difficult to understand and predict the plasma discharge behavior. One of the topic is that electron mobility across the imposed magnetic field in the channel discharge is anomalously high in comparison to predictions from classical diffusion theories. Multiple mechanisms have been proposed: Secondary electron emissions, sheath instabilities, gradient driven instabilities, or electron drift instabilities. Effect of these drift instabilities on the electron mobility has been recently investigated theoretically, and compared to $r - \theta$ simulations using a simplified 2.5D PIC simulation model. However in these simulations, walls were assumed to be metallic with no secondary electron emission. In this work we compare results obtained with metallic and dielectric walls, with and without secondary electron emissions (using various models). These improvements enable a deeper look into the behavior of the thruster operation, and allow us to differentiate the relative importance of the mechanisms producing enhanced electron transport.

*Safran Aircraft Engines/ANRT.

14:15

MW3 4 The role of instability-enhanced friction on electron transport in E x B discharges TREVOR LAFLEUR, PASCAL CHABERT, *LPP, Ecole Polytechnique* The applied discharge voltage and magnetic field in many E×B discharges produces large electron drift velocities that can drive plasma instabilities leading to increased particle transport. Here we present self-consistent 2D particle-in-cell (PIC) simulations investigating such instabilities in typical ExB discharges such as Hall-effect thrusters. The PIC simulations preserve fundamental plasma spatial and temporal scales and do not include any artificial geometric or parametric scaling factors. Short-wavelength, high-frequency, oscillations are observed to form just a few microseconds after the discharge begins and with a Fourier spectrum that matches that for an ion acoustic-type instability (in agreement with kinetic theory). Correlated with the presence of this instability is an increased electron cross-field transport that cannot be explained by standard electron-neutral or electron-ion Coulomb collisions. By taking velocity moments of the electron distribution function in the PIC simulations, we reconstruct each term in the electron momentum conservation equation and demonstrate that "anomalous" electron transport in such discharges can be explained entirely due to an instability-enhanced friction force between electrons and ions. This friction force acts as an additional momentum loss mechanism aiding electron transport, and as an ion acceleration mechanism causing both rotation and heating.

Invited Papers

14:30

MW3 5 Multi-dimensional PIC modelling of crossed-fields low temperature plasma devices
FRANCESCO TACCOGNA, *CNR-Nanotec - P.Las.M.I. Lab*

Different plasma devices are based on the partial magnetisation of electrons in a ExB configuration. In Hall thrusters, a quasi-radial magnetic field creates a strong impedance to the axial electron transport, making a path from the external cathode to the internal anode-gas distributor longer. This increases the ionisation event chances and at the same time it creates a large electron azimuthal drift and virtual cathode for axial ion acceleration. In negative ion source, the tandem-magnetic barrier concept is often used and it consists of using a perpendicular to the flow magnetic field trapping electrons in order to reduce their density and temperature towards the extraction grid region. This reduces the negative ion destruction by electron detachment and the co-extracted electron current. In all the cases, a larger electron current across the magnetic field is measured and often ascribed to an anomalous (non-collisional) character of the transport. By means of multi-dimensional Particle-in-Cell / Monte Carlo Collision (PIC-MCC) models, we have shown how plasma uses all the different dimensions to create self-organised potential structures to increase the limited transport across B field lines.

Results show the non-ambipolar character of the transport driven by electron magnetic drifts. Finally, the walls of the device play the role of short-circuiting the electron flow that exhibits a quite complex distribution.

Contributed Papers

15:00

MW3 6 Magnetohydrodynamic simulation study of plasma jets and plasma-surface interactions in coaxial plasma accelerators VIVEK SUBRAMANIAM, LAXMINARAYAN RAJA, *The University of Texas at Austin* Coaxial plasma accelerators belong to a class of electromagnetic acceleration devices that utilize the Lorentz force generated by self-induced magnetic fields to accelerate high density thermal plasmas to large velocities (10Km/s). A MHD simulation study of the coaxial plasma accelerator is performed to elucidate the physical mechanisms responsible for the formation of these hypervelocity plasma jets. Distinct modes of jet-formation are identified based on the prefill conditions in the accelerator. The plasma jet is used as a high energy density source to mimic the extreme stagnation conditions generated on the confining walls of fusion reactors during Edge Localized Mode (ELM) type disruption events. This is achieved by impinging the jet on a target material surface placed normal to the jet trajectory. The MHD simulations are used to resolve the transient shock structure that develops on the target surface during the course of the plasma-surface interaction event. The jet-target impact studies indicate the existence of two distinct stages involved in the plasma-surface interaction. A fast transient stage characterized by a thin normal shock that transitions into a pseudo-steady stage that exhibits an extended oblique shock structure.

SESSION NW1: POSTER SESSION II
Wednesday Afternoon, 8 November 2017
Exhibit Salon ABC at 16:00

NW1 1 Electron stopping powers in H_2* MARK ZAMMIT, *Los Alamos National Laboratory* DMITRY FURSA, ROBERT THRELFALL, JEREMY SAVAGE, IGOR BRAY, *Curtin University* Electron stopping power (STP) is an important parameter of interest in medical and environmental applications. Accurate evaluation of the electron STP in molecules requires a complete set of electron impact cross sections for all important reaction channels including excitation, ionization and dissociation. These data have recently been calculated for electron scattering on the ground state of molecular hydrogen with the convergent close-coupling (CCC) method [1,2], for incident electron energies up to 300 eV. Here we extend the CCC calculations to 2000 eV and apply the CCC collision data to calculate the electron STP in molecular hydrogen. At high energies our results are in good agreement with the Born-Bethe theory available from the NIST database [3]. Comparison with the mean excitation energy that was directly measured by Muñoz *et al.* [4] showed excellent agreement.

*This work was supported by Curtin University, The Pawsey Supercomputing Centre, Los Alamos National Laboratory, and the United States Air Force Office of Scientific Research.

[1]M. C. Zammit *et al.*, Phys. Rev. Lett. **116**, 233201 (2016).
[2]M. C. Zammit *et al.*, Phys. Rev. A **95**, 022708 (2017).
[3]Stopping power and range tables for electrons http://physics.nist.gov/PhysRefData/Star/Text/method.html.
[4]A. Muñoz *et al.*, Chem. Phys. Lett. **433**, 2614 (2007).

NW1 2 Calculation of electron scattering on silver* DMITRY FURSA, KEEGAN MCNAMARA, IGOR BRAY, *Curtin University* The relativistic convergent close-coupling (RCCC) method has been applied to study electron scattering from silver and obtain differential and integrated cross sections for elastic scattering and excitation to the $4d^{10}5p$, $4d^{10}6s$, $4d^{10}6p$, $4d^{10}5d$, $4d^{10}7s$, and combined $4d^{10}7p$, $4d^{10}6d$, and $4d^{10}4f$ states for incident electron energies up to 500 eV. In addition to the cross sections we have obtained Stokes parameters for the $(4d^{10}5p)^2P_{3/2}$ state and elastic spin asymmetries. The silver atom is described by a model of a single electron above a frozen [Kr]$4d^{10}$ core. Empirical one- and two-electron polarization potentials have been used to obtain the best representation of the target state energies and the optical oscillator strengths. To test convergence we have conducted calculations using a number of models and present results for two target states models, one consisting of 22 bound states and 28 continuum states, and the other extending the number of continuum states to 58. Good agreement was found with available experimental data for elastic scattering and $4d^{10}5p$ excitation differential cross sections.

*Work supported by Curtin University and Pawsey Supercomputing Centre.

NW1 3 Transition rates and electron impact excitation rates for O III* SWARAJ TAYAL, *Clark Atlanta University* OLEG ZATSARINNY, *Drake University* Transitions probabilities, electron excitation collision strengths and rate coefficients for a large number of O III lines have been calculated in the close-coupling approximation using the B-spline Breit-Pauli R-matrix method. The multiconfiguration Hartree-Fock method is employed for an accurate representation of the target wave functions. The close-coupling expansion contains 202 O III fine-structure levels comprising the 5 levels of the ground configuration $2s^22p^2$, 10 levels of first excited configuration $2s2p^3$, 4 levels of the $2p^4$ configuration, all levels for the 2p excitation to the $2s^22p3s$, 3p, 3d, 4s, 4p, 4d, 4f, 5s configurations, and all levels for the 2s excitation to the $2s2p^33s$,3p,3d configurations. The collision strengths have been calculated for the 20302 transitions between all 202 fine-structure levels. There is an overall good agreement with the recent R-matrix calculations by Ref. [1] for the transitions between first 5 levels of the ground $2s^22p^2$ configuration, but significant discrepancies have been found with Ref. [2] for transitions to the $2s^22p^2$ $^1S_0$ level. A fair agreement is found with the LS-coupling calculation of Ref. [3] for transitions to the $2s^22pnl$ states, with average discrepancies of about 30%. However, rate coefficients differ by up to a factor of 10 for some transitions. The present calculations provide data sets that should allow a more detailed treatment of the available measured spectra from different space observatories [1–3].

*This research work is supported by the National Science Foundation Grant Number 1714159.

[1]P. Storey *et al.*, MNRAS **441**, 3028 (2014).
[2]E. Palay *et al.*, MNRAS **423**, L35 (2012).
[3]K. Aggarwal and F. Keenan, ApJS **123**, 311 (1999).

NW1 4 Electron Impact Excitation of He, H_2 and Ar* MERL MARTIN, ROBERT WRIGHT, LEIGH HARGREAVES, MURTADHA KHAKOO, *California State University Fullerton* Angle-differential electron impact excitation of He, Ar, H_2 and H_2O will be presented at low energies using a time-of-flight electron spectrometer which employs pulsing of a grid in front of the electron filament source. The data will be presented for energies close to threshold for excitation to about 20eV above threshold and will be compared to existing theory.

*Funded by NSF-RUI AMOP Program.

NW1 5 Electron Impact Excitation of the Electronic States of H_2* LEIGH HARGREAVES, MURTADHA KHAKOO, *California State University Fullerton* Differential electron scattering cross-sections for electron scattering from H_2 at low energies are presented for the lowest five bound electronic states of H_2. The data will be compared with the recently developed successful convergent close-coupling theory for H_2.

*Funded by the NSF-RUI AMOP Program.

NW1 6 Electron Impact Excitation of CO* MURTADHA KHAKOO, LUCA RATKOVIC, LOGAN VOORNEMAN, *California State University Fullerton* Extensive differential cross-sections for the electron impact excitation of CO for electronic states from 6 eV to 1.5 eV are presented. The data were taken for electron scattering angles from 10° to 120° and impact energies from 6.1 eV to 20 eV. The data were obtained by unfolding the energy loss spectra of CO taken t these energies and scattering angles.

*Funded by the NSF-RUI AMOP Program.

NW1 7 Laser assisted free-free experiments: the search for dressed-atom effects* C.M. WEAVER, B.N. KIM, N.L.S. MARTIN, *University of Kentucky* B.A. DEHARAK, *Illinois Wesleyan University* The absorption or emission of radiation during the collision of charged particles with atoms and molecules is investigated in the so-called free-free experiments. Up to now almost all such experiments have been in agreement with a simple theory which assumes that the interaction of the radiation with the atom itself has no effect on the scattering process. Very recently the first experiments to observe the unambiguous breakdown of this assumption have been carried out in xenon by Morimoto, Kanya, and Yamanouchi [1]. An estimate of the dressing of the target by the radiation's electric field may be made in terms of the electric dipole polarizability of the target. The effects in Xe were extremely difficult to measure because they occur at very small scattering angles. We have begun to carry out laser-assisted elastic scattering experiments in potassium, and laser-assisted inelastic scattering experiments in argon. In both cases we expect that dressing effects should be observed at scattering angles easily accessible to experiments, and without the need for complicated corrections.

*This work was supported by the National Science Foundation under Grants Nos. PHY-1607140 (NLSM), PHY-1402899 (BAd).

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NW1 8 Accurate Gaseous Ion Mobility Measurements LARRY VIEHLAND, ANBARA LUTFULLAEVA, JAMIYANAA DASHDORJ, *Chatham University* RAINER JOHNSEN, *University of Pittsburgh* The accuracy of experimental measurements of gaseous ion mobility has not improved for decades, and it is still generally 2-5%. It is shown that theoretical values of the mobility of atomic ions in atomic gases can be used to calibrate a drift-tube mass spectrometer, leading to subsequent measurements that are accurate to 0.6% for He+ in He near room temperature as the ratio of the electrostatic field strength to the gas number density ranges up to 200 Td. Values of the ratio of the parallel diffusion coefficient to the mobility are also reported.

NW1 9 Electron drift velocity and density-reduced effective ionization coefficient in pure chlorine* OLMO GONZÁLEZ-MAGAÑA, JAIME DE URQUIJO, *Instituto de Ciencias Físicas UNAM* Swarm experiments in chlorine gas (Cl_2) are remarkably scarce. To the best of our knowledge, only two experimental studies of swarm parameters for Cl_2 have been reported. Bozin and Goodyear [1] measured the coefficients α/N, η/N, and $(\alpha - \eta)/N$ in Cl_2. Another measurement of η/N was made by Bailey and Healey [2]. They also reported the only known measurements of electron drift velocity (W) for chlorine using mixtures of Cl_2 with He. Clearly, there is some controversy among the low-energy plasma community for the reliability of these only available data and, therefore there is a need for new measurements. This lack of data is mainly due to the serious technical challenges for the experiment because of the highly corrosive, toxicity and electronegativity of gaseous chlorine. To solve this problem, we have designed and built a new discharge apparatus based on the pulsed -Townsend method and made of glass walls. We report on our recent swarm experiment for electrons in pure chlorine and its mixtures with N_2. Measurements were made on electron drift velocity and density-reduced effective ionization coefficient and compared with the previously measured and calculated data.

*This work is supported by CONACyT, Grant 240073 and PAPIIT-UNAM, IN108417. Thanks are due to A. Bustos and G. Bustos for their technical support. OGM thanks CONACyT for a postdoctoral fellowship.

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NW1 10 Measurements of angular-resolved ion velocity distribution functions* VLADIMIR SOUKHOMLINOV, *Saint Petersburg State University, Saint Petersburg, Russia* ALEXANDER MUSTAFAEV, *Saint Petersburg Mining University, Saint Petersburg, Russia* IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory, Princeton, USA* Flat probe can be used for measurements of the angular-resolved (anisotropic) ion velocity distribution function (IVDF). The variation of the sheath area around the probe was determined analytically; and effective collecting area of the probe was obtained and taken into account for corrections to the second derivative of current–voltage characteristics. Experimental measurements of IVDF for He^+ in He, Ar^+ in Ar and Hg^+ in Hg were performed [1–3] and compared with Monte Carlo simulations [4,5]. Good agreement between two was obtained.

*Work supported in part by a USA Department of Energy.

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WEDNESDAY AFTERNOON \ NW1

NW1 11 Probe measurements of angular-resolved electron velocity distribution functions ALEXANDER MUSTAFAEV, *Saint Petersburg Mining University, Saint Petersburg, Russia* VLADIMIR SOUKHOMLINOV, *Saint Petersburg State University, Saint Petersburg, Russia* OSCAR MURILLO, *Saint Petersburg Mining University, Saint Petersburg, Russia* IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory, Princeton, USA* We investigate operation of the flat probe for measurements of the anisotropic electron velocity distribution function (EVDF). Particular attention was given to the limiting case of very narrow angular EVDFs (beam-like EVDF). A new algorithm for analysis of the flat probe data was developed, which does not involve integral relation. Method was verified for EVDF in low pressure, low voltage beam discharge in hollow cathode, where two beams ejected from the side and back walls of the hollow cathode form very anisotropic EVDF. Advantage of the new methodover traditional method was demonstrated. Experimental measurements of EVDF were performed and compared with Monte Carlo simulations.

NW1 12 N_2H^+ recombination with electrons in low temperature afterglow plasma* PETR DOHNAL, ABEL KALOSI, DMYTRO SHAPKO, RADEK PLASIL, JURAJ GLOSIK, *Faculty of Mathematics and Physics, Department of Surface and Plasma Science, Charles University, Prague, Czech Republic* RAINER JOHNSEN, *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania 15260, United States* A study on N_2H^+ recombination with electrons in afterglow plasma is presented. The cavity ring-down absorption spectroscopy in continuous wave modification was used as a principal diagnostics tool to probe number densities of several rotational states of the ground and the lowest excited vibrational state of the N_2H^+ ion. The recombination rate coefficients were measured at 300 K in afterglow of a microwave discharge ignited in a mixture of $He/H_2/N_2$ and of H_2/N_2 with typical number densities on the order of $10^{17}/10^{14}/10^{14}$ cm^{-3} and $10^{17}/10^{14}$ cm^{-3}, respectively. The dependencies of the measured recombination rate coefficient on number densities of He and H_2 were evaluated to obtain upper limit for three body recombination rate coefficient of N_2H^+.

*This work was partly supported by Czech Science Foundation projects GACR 17-08803S, GACR 15-15077S and GACR 17-18067S.

NW1 13 Positron scattering from helium ALLAN STAUFFER, *York University* ROBERT MCEACHRAN, *Australian National University* We present scattering results for positron-helium scattering for energies from zero to 1 keV. These have been calculated using our complex optical potential method [1]. Positronium formation was calculated using the technique reported in [2]. Integrated cross sections are given for elastic, inelastic, ionization, positronium formation and total scattering. These are compared with experimental and other theoretical results and good agreement is obtained except in the case of ionization below the peak of the cross section.

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NW1 14 Imposed ordered structure in magnetized discharge* PETER HARTMANN, *Wigner Research Centre for Physics; CASPER at Baylor University* First experimental findings obtained with the new Magnetized Dusty Plasma Experiment (MDPX at Auburn University) include the formation of ordered structures in high vertical magnetic fields (>1 T) imposed by the wire-grid upper horizontal electrode and visualized by micrometer dust particles levitating on top of the lower flat electrode sheath of a capacitively coupled RF discharge [1]. Simple arguments based on charged particles being confined to helical trajectories along the magnetic field lines are not sufficient because all relevant collision processes have mean free paths well shorter than the distance between the structured electrode and the lower electrode sheath. We apply our newly implemented 2.5 dimensional GPU accelerated particle in cell (PIC) discharge simulation both for cylindrical geometry to compute global discharge parameters and with cartesian symmetry for the determination of local plasma parameters including the charging and force balance computation of the dust particles with high resolution. The PIC simulations will reveal the microscopic details of how the spatial structure of the upper electrode can migrate through the bulk plasma and influence the structure of the lower sheath region.

*Supported by NKFIH Grant K-115805.

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NW1 15 Application of a large wall probe in a short dc discharge as a gas analytical detector for high-energy atomic and molecular processes V. I. DEMIDOV, *West Virginia University* S. F. ADAMS, *AFRL* M. E. KOEPKE, *West Virginia University* A. A. KUDRYAVTSEV, *St. Petersburg State University* I. P. KURLYANDSKAYA, *INTEPH Technologies LLC* J. A. MILES, *AFRL* An approach, which is based on the measurements of the electron energy distribution function (EEDF) with a large electric wall probe in a short (without positive column) dc discharge, can lead to the development of gas analytical detectors [1]. In this work, a short dc discharge with cold cathode and conducting walls was used in experiments at gas pressures of a few Torr to measure fine structures associated with atomic and molecular plasma processes at the high-energy portion of the EEDF in the plasma. It is experimentally demonstrated that for the investigated conditions the maxima associated with plasma-chemical reactions at the EEDF are proportional to the second derivative of electron current with respect to the probe potentials. Measurements have been conducted in helium gas and helium-argon gas mixtures with content of argon from 0.002% to 5%. Calibration of the device for the absolute measurements of densities of plasma constituents has been demonstrated. It is shown that the presence of a specific target gas component can be monitored from the measured EEDF.

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NW1 16 Dielectric-directed surface flashover under atmospheric conditions* PAUL CLEM, LAURA BIEDERMANN, CHRIS MOORE, *Sandia National Laboratories* ELECTRICAL SCIENCES TEAM High-voltage arc formation near a dielectric material is a complex process by which surface charging, secondary electron emission, and photoelectron emission modify the local electric field to determine the arc path and breakdown threshold. Strong electric field enhancement at the triple-point junction of dielectric, metal, and atmosphere may act to generate initiating electrons to seed prompt formation of streamers. This study investigates the dielectric role in influencing voltage breakdown threshold and reproducibility under high voltage conditions with and without external ultraviolet stimulation. We investigate effects of varying dielectric permittivity, and whether and how field emission at triple points can minimize variance in atmospheric breakdown behavior. Using a low-inductance test-stand, 200 micron dielectric granules were placed on a planar brass electrode in dry air at 600-Torr, opposite rounded brass rod electrodes which defined 0.25mm to 1-mm gaps. Polarity-dependent breakdown measurements (V, I) and images were collected as a function of granule permittivity and voltage polarity. We will discuss data and models of how dielectric material properties impact surface charging, electron emission, and ionization, thereby directing the flashover path.

*Sandia National Laboratories is a multimission laboratory managed and operated by NTESS LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE NNSA under Contract DE-NA0003525.

NW1 17 Pressure Effects on Double Layer Accelerated Ion Beams in Multi-Species Helicon Plasmas EVAN AGUIRRE, *West Virginia University* TIMOTHY GOOD, *Gettysburg College* EARL SCIME, *West Virginia University* Double layers are free-standing sheath like structures that are observed to form spontaneously in expanding, high-density plasmas, thereby accelerating ions to supersonic speeds. We use laser induced fluorescence to measure the parallel ion flow speeds of multi-species helicon plasmas immediately downstream of a current free double layer. Steady state, low pressure plasmas are created with three different gas mixtures; argon and xenon, argon and helium, xenon and helium. A helium ion LIF scheme does not exist, so we are confined to measuring the ion velocity distribution functions of argon and xenon. Contrary to observations in mixed gas sheath experiments, our measurements show that adding a lighter gas does not increase the ion beam speed, In fact, the heavy ion speed decreases. Thus, we find that different ion species fall through the double layer at their own Bohm speed rather than an average of their speeds, regardless of the relative densities of the ion species. Pressure effects are the dominant factor for ion beam speed; increasing pressure slows all ion beams.

NW1 18 The Influences of the Wall Material Arrangement of Ionization Region on the Discharge Characteristics of the Hall Thruster Channel* PING DUAN, LONG CHEN, XINGYU BIAN, XIANG HU, WENQING LI, *Dalian Maritime University* Hall thruster plasma has strong interactions with the channel wall, which significantly affect the discharge performance of the thruster, In this work, a two-dimensional physical model is established based on the discharge process of Hall thruster discharge channel. PIC method is applied to study the influences of segmented low emission graphite electrodes with biased voltage on discharge characteristics of the Hall thruster channel. The influences of segmented electrode arranged in the ionization region on electric potential, ion number density, electron temperature, ionization rate, discharge current and impulse are discussed. The results show that, when the segmented electrode is arranged at different positions in the ionization region, the axial length of the acceleration region is obviously shortened, the potential line is perpendicular to the wall, and the channel wall corrosion decreases along with the radial velocity reduction. As the position of the segmented electrode moves towards the acceleration region, the axial peak position of electron temperature moves towards the exit. The collision frequency between the electrons and the wall increases, the ionization rate is enhanced, the discharge current declines, eventually the impulse of thruster is improved.

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11605021,11375039).

NW1 19 Electron Avalanche and Streamer Processes Near a Dielectric Interface with Variable Photo-Electron Emission* ASHISH JINDAL, CHRIS MOORE, ANDREW FIERRO, ROY JORGENSON, *Sandia National Laboratories* The effects of secondary photo-electron emission from a dielectric surface on electron avalanche and streamer processes are modeled in air at 760 Torr via an electrostatic PIC code which simulates particle-particle collisions using the DSMC method. A quasi-neutral seed plasma is placed near the cathode end of a 2 mm gap. The air chemistry model [1] includes Townsend breakdown and streamer mechanisms, tracking excited state neutrals that can either undergo quenching collisions or spontaneous photon emission transitions [2]. Initial results suggest that photoemission can significantly affect streamer evolution along the dielectric [3].

*Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE NNSA under Contract DE-NA00035.

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[3] A. Jindal *et al.*, "Streamer Formation Near a Dielectric Surface with Variable Quantum Efficiency", ICOPS 2017.

NW1 20 Study on the radical production in atmospheric pressure plasma jets operated by nanosecond pulses YOUBIN SEOL, BYUNGKEUN NA, HONGYOUNG CHANG, *Korea Advanced Institute of Science and Technology* Applications of plasma discharges for bio-medical uses are rapidly growing area. Atmospheric pressure plasmas have various advantages in bio-medical applications from sterilization to coagulation or skin regeneration. Atmospheric pressure plasma jets are one of the common atmospheric pressure plasma sources, which have unique virtue in the utility and the local treatment. The radicals produced from plasma discharge have important roles in plasma - bio interactions. It can enhance the cell proliferation and also cause cell death. The pulsed operation of plasma was introduced for bio-treatment, which can reduce the heat and enhance the radical production with better power efficiency. In pulsed plasma jets, the pulse characteristics changes the plasma operation and the radical productions. Currently, using nanosecond pulses are growing with its high efficiency. The experiment was performed by changing the pulse width in nanosecond range and measuring the radical production. The effect of the pulse characteristics on the radical production was studied. The computational simulations of chemical reactions were also accomplished which supplements the experimental results.

NW1 21 The influence of the pulse duration and the duty ratio on the discharge characteristics of helium and argon atmospheric pressure plasma jets TIANYU TANG, HYUNYOUNG LEE, *Pusan National University* GUANG-HOON KIM, BYUNG-HAK LEE, *Korea Electrotechnology Research Institute* HAE JUNE LEE, *Pusan National University* Atmospheric pressure plasma jets (APPJs) have been widely used for biomedical applications for the last couple of decades. Most of APPJs are operated with the sinusoidal driving voltage at a frequency range of tens of kHz to MHz. In this study, we present the properties of monopolar pulse-driven APPJs which show different performances from those with sinusoidal driving voltages. The pulse duration has been varied from hundred nanoseconds to hundreds of microseconds, and the duty ratio is also varied. Experimental investigation of APPJ includes optical emission spectrometry (OES) and the current-voltage characteristics. In this presentation, a global simulation model was used to compare electron temperature, electron density and electron energy density of helium and argon gas plasma jet. In the experiment, the relationship between the plasma parameters and the breakdown voltage was investigated. Also, OES was used to investigate the radical components and to calculate the electron temperature.

NW1 22 Charging characteristics of dust grains in different plasma environments* LONG CHEN, PING DUAN, XINGYU BIAN, WENQING LI, *Dalian Maritime University* Dust particles are exist in space, earth atmosphere, industrial production and laboratory, and also charged by plasmas. Charged dust in plasma environment has been widely studied in various scientific research fields, such as the charge and discharge of dust, dust and impurities in Tokamak boundary transport, dust crystal, space debris charging and utilization etc. The charging model in the plasma environment of dust mainly used the OLM theory, but with the complicated plasma environments, relaxation process of dust particle charging and the final saturation electron quality and potential will be distinct. For example, in the tokamak dust grains are charged by plasma with a strong macro velocity; in the space environment, dust debris particles charging are not only determined by plasmas, but also by high-energy particle radiation, magnetic field, secondary electron emission, ultraviolet ray and so on. Therefore, it is of great significance to study the charge relaxation process of dust particles under different circumstances.

*Project supported by the National Natural Science Foundation of China (Grant Nos. 11605021,11375039).

NW1 23 Comparison of algorithms for numerical optimization of chemical reaction rate coefficients in plasma simulation SANG-YOUNG CHUNG, DEUK-CHUL KWON, *Plasma Technology Research Center, National Fusion Research Institute* For a reliable plasma simulation accurate rate coefficients for chemical reactions are important. The set of the rate coefficients should include essential reactions like appearing and disappearing of main species. However, some of them are hard to achieve from literature survey, experiments or calculations. Then, researchers have been estimated the missing rate coefficients and looked for proper rate coefficients until the simulation results agree with experiments. These searching process can be done by researchers with trial and error method, but can be done by numerical optimization method with less human efforts. In this study rate coefficients were numerically optimized with several algorithms including steepest descent, Newton, modified Newton and Broyden-Fletcher-Goldfarb-Shanno algorithms. A spatially averaged global code were used to simulate plasma while numerical optimizations. The accuracy and efficiency of algorithms were compared with each other. The methods to determine initial starting point of the optimization were also discussed.

NW1 24 Comparison of Zero Dimensional Plasma Chemistry Model with Ozone Absorption Spectroscopy Measurements* RYAN T. SMITH,† EFE KEMANECI, *Theoretische Elektrotechnik Ruhr-Universität Bochum* BJOERN OFFERHAUS, FRIDERIKE KOGELHEIDE, NIKITA BIBINOV, PETER AWAKOWICZ, *Allgemeine Elektro- und Plasmatechnik Ruhr-Universität Bochum* RALF PETER BRINKMANN, *Theoretische Elektrotechnik Ruhr-Universität Bochum* KATHARINA STAPELMANN,‡ *Nuclear Engineering - North Carolina State University* Results from zero dimensional computer simulations are compared to absorption spectroscopy measurements of Ozone within the gas phase of a Surface Dielectric Barrier Discharge (SDBD) and a Volumetric Dielectric Barrier Discharge (VDBD). The simulation model consists of two interdependent zero dimensional models that span two time scales and spatial regimes. The model incorporates 53 reactive species and 624 reactions to simulate the chemical dynamics of an atmospheric pressure plasma discharge in humid Nitrogen/Oxygen mixtures. The separation of the reactive species into long and short lived species allows for speedy simulations of the gas phase dynamics while still being directly coupled to the discharge dynamics. Comparisons are made at varying gas mixtures, supplied voltage frequencies and amplitudes. Although the computational model does not provide spatially resolved results nor directly comparable results, generalizations can be obtained and predicted. Furthermore, this work easily leads to the expansion of the model to provide more accurate and physically representative results.

*SFB-TR 87/2.

†Also Affiliated with Allgemeine Elektro- und Plasmatechnik Ruhr-Universität Bochum.

‡Also Affiliated with Allgemeine Elektro- und Plasmatechnik Ruhr-Universität Bochum.

NW1 25 Development of atmospheric high-speed jet pulsed plasma source for high-speed surface treatment DAISUKE OGASAWARA, HIROAKI KAWANO, HIDEKAZU MIYAHARA, *FIRST, Tokyo Institute of Technology* CHIAKI SATO, *MSL, Tokyo Institute of Technology* AKITOSHI OKINO, *FIRST, Tokyo Institute of Technology* In recent years, atmospheric non-thermal plasmas have been widely used for surface treatment such as pretreatment for adhesion strengthening. However, in conventional remote plasma sources, many reactive species lose the surface treatment effect before they arrive to the target surface because they have short lifetime. For this reason, usual plasma sources could give the effect in short-distance of about several mm, and they have limitation in processing speed. To solve this problem, we developed an atmospheric high-speed jet pulsed plasma source. In this source, high-density plasma generated in continuous low gas flow is irradiated by high-speed short-pulsed gas flow and so reactive species arrive to the remote surface in a short time. In the experiment, a high-pressure gas valve of 0.5 MPa was opened for 0.1 s to generate the high-speed gas flow. Nitrogen plasma pulsed jet was irradiated once per second at 5 mm of working distance. The plasma gas velocity was measured by Schlieren method and the surface treatment effect was evaluated by water contact angle. Consequently, the maximum gas velocity was 490 m/s (Mach 1.4) and the hydrophilization speed had improved to twice compared to our conventional plasma source.

NW1 26 The role of secondary electron emission in capacitive rf plasmas at low pressure* BIRK BERGER, *BTU Cottbus-Senftenberg, Germany; Ruhr-University Bochum, Germany* JULIAN SCHULZE, PETER AWAKOWICZ, *Ruhr-University Bochum, Germany* THOMAS MUSSENBROCK, *BTU Cottbus-Senftenberg, Germany* ARANKA DERZSI, BENEDEK HORVÁTH, ZOLTÁN DONKÓ, *Wigner Research Centre for Physics, Hungary* The correct choice of the ion induced secondary electron emission coefficient, γ, is of high importance to obtain realistic results by PIC/MCC-simulations of capacitive rf plasmas. In most studies, this coefficient is set to $\gamma = 0.1$ without taking into account the energy of the incident particles, the electrode material, and the surface conditions. Recently, studies showed that using a more realistic, energy dependent γ-coefficient strongly influences the outcome of computational investigations at high pressure. In CCPs used for sputtering a much lower pressure of approx. 1Pa is used. In this regime, the plasma-surface interaction can lead to a change of the surface conditions, e.g. by target poisoning. This can result in process drifts. This effect is usually linked to the change of γ but it is not understood how γ affects the plasma at such low pressures, where the multiplication of secondary electrons within the sheath is negligible. This work investigates the effect of different γ-coefficients on the discharge by PIC/MCC-simulations at low pressures in argon. It is found that the confinement of γ-electrons by multiple reflections at the sheaths strongly influences the ionization rate.

*This work is supported by the US NSF Grant 1601080, by the German DFG SFB TR 87 Grant, and Hungarian Grants K-119357 and PD-121033.

NW1 27 The effects of surface characteristics on the spatio-temporal excitation dynamics in capacitive RF plasmas studied by PROES* STEVEN BRANDT, *Department of Physics, West Virginia University, USA* JULIAN SCHULZE, BIRK BERGER, *Department of Physics, West Virginia University, USA; Insitute for Electrical Engineering, Ruhr-University Bochum, Germany* MARK KOEPKE, *Department of Physics, West Virginia University, USA* DOUGLAS KEIL, *Lam Research Corporation, Tualatin, USA* In commercial capacitively coupled radio frequency plasmas (CCPs), surface characteristics can change as the chamber conditions drift between clean cycles. The effects of these drifts on the electron heating dynamics and, consequently, on plasma parameters are unclear. In order to clarify these effects we place aluminum discs with varying surface roughness or AlF film thickness on the powered electrode of a GEC reference cell and study their effects on the spatio-temporal electron impact excitation dynamics by Phase Resolved Optical Emission Spectroscopy (PROES). Measurements are performed in argon plasmas driven at 13.56 MHz and at different pressures as well as voltages. Special attention is paid to effects induced by a change of the secondary electron emission coefficient as a function of surface roughness and film thickness traced by monitoring the relative intensity of electron impact excitation induced by sheath expansion heating and by secondary electrons.

*Funding: US NSF Grant No 1601080. Support from Lam Research Corporation is acknowledged.

NW1 28 A novel cupping-assisted plasma treatment for skin disinfection ZILAN XIONG,* *Huazhong University of Science and Technology* A novel plasma treatment method/plasma source called cupping-assisted plasma treatment/source for skin disinfection is introduced. The idea combines ancient Chinese 'cupping' technology with plasma sources to generate active plasma inside a reduced-pressure chamber attached to the skin. Advantages of this scheme include reducing the threshold voltage for plasma ignition and improving the spatial uniformity of the plasma treatment. In addition, the reduced pressure inside the cup should improve skin pore permeability and it simplifies attachment of the plasma device to the skin. Moreover, the plasma-generated active species are restricted inside the cup, raising local reactive species concentration and enhancing the measured surface disinfection rate. A surface micro-discharge (SMD) device is used as an example of a working plasma source. We report discharge characteristics as a function of pressure and applied voltage. When using a relatively low applied voltage, the antibacterial effect under reduced pressure showed enhanced antibacterial effects and was comparable with discharges operated at atmospheric pressure under higher voltage.

*The Affiliation of the author should be the one where the author will work in Nov. 2017.

NW1 29 Kinetic treatment of plasma-material interactions utilizing dynamically-coupled Boltzmann plasma and surface erosion model SHANE KENILEY, DAVIDE CURRELI, *Univ of Illinois - Urbana* We present a numerical characterization of plasma-surface interaction by using a multi-species full-f Boltzmann plasma description coupled to a Binary Collision Approximation (BCA) model, Fractal-TRIDYN. The method couples a continuum Boltzmann-Poisson solver of a multi-species plasma to an improved version of the TRIDYN code including dynamic surface composition. The BCA module provides on-the-fly boundary conditions for a complete description of the dynamic feedback between the near-wall plasma and the material surface. Kernel density estimates are utilized to reconstruct continuous distributions from the discrete data predicted by the BCA model. Phenomena such as material sputtering, backscattering, and implantation, and their effect on the structure of the near-wall plasma, are dynamically accounted for in both mono-component and multi-component targets.

NW1 30 Diagnostics of Diffuse Large Volume Plasma Generated by an External Ionization Wave HAMID RAZAVI, MOUNIR LAROUSSI, *Old Dominion University* Atmospheric pressure low temperature plasma jets are the product of guided ionization waves. Guided ionization waves can be transmitted through a dielectric material and under some conditions can ignite a discharge behind the dielectric material. We have recently reported on a novel way to produce large volume diffuse low pressure plasma inside a Pyrex chamber that does not have any electrodes or electrical energy directly applied to it. The diffuse plasma is ignited by a plasma jet located externally to the chamber. The plasma jet is placed in close proximity to the external wall/surface of the chamber or to a dielectric tubing connected to the chamber. The plasma ignited inside the chamber is diffuse, large volume and with physical and chemical characteristics that are different than the external plasma jet that ignited it. Here, we present diagnostics of the reduced pressure diffuse plasma including electron density and temperature, using Langmuir probe, fast imaging to study the propagation of the ionization wave inside the chamber and the plasma structure, and optical emission spectroscopy to identify the emitting excited species.

NW1 31 Burning modes of a bipolar pulse discharge in CO_2 and nitrogen V.A. LISOVSKIY, S.V. DUDIN, N.N. VUSYK, A.N. DAKHOV, V.D. YEGORENKOV, *Kharkov National University, Kharkov, Ukraine* P.A. OGLOBLINA, *Instituto de Plasmas e Fusao Nuclear, Lisboa, Portugal* This paper reports the current and voltage oscilloscope patterns of the bipolar pulsed discharge in the frequency range (from 20 to 300 kHz) with the duty cycle from 0.11 to 0.97 that have been measured in CO_2 and nitrogen within the pressure range from 0.1 to 1 Torr. It has been found that varying the duty cycle may change the discharge axial structure and redistribute the potential drop across the electrodes. At large duty cycle values the discharge has been found to experience a transition from the conventional high-current mode (with cathode sheaths near both electrodes) to a low-current mode characterized by low discharge current values and a feeble glow. In this mode the ionization takes place only in the cathode sheath and the negative glow near the electrode at the time period to which the high voltage is applied. During the remaining part of the period a lower voltage is applied to the second electrode which is insufficient for the cathode sheath formation, therefore during this time one observes a decaying plasma (afterglow). The radiation spectra of the bipolar pulsed discharge in nitrogen have been measured at different duty cycle values using the optical spectrometer. It has been revealed that in a low-current mode the ionization occurs predominantly near one electrode whereas the cathode sheath is not formed near another electrode.

NW1 32 Electric field non-uniformity effect on dc low pressure gas breakdown between parallel plate electrodes V.A. LISOVSKIY, R.O. OSMAYEV, A.V. GAPON, V.D. YEGORENKOV, *Kharkov National University, 61022, Kharkov, Svobody Sq. 4, Ukraine* This paper presents the results of studying the gas breakdown in a non-uniform direct current electric field. The breakdown curves have been measured in nitrogen between flat electrodes of 12 mm in diameter spaced 3 to 300 mm apart and placed inside the discharge tubes of 13 mm and 56 mm in diameter. The effects of the non-uniform distribution of the electric field inside the inter-electrode gap and of the diffusion loss of charged particles to the discharge tube walls on the gas breakdown have been studied separately. A conclusion is drawn from the experimental data that the general form of the gas breakdown criterion must be as follows $U = f(pL, L/R_{el}, L/R_{\rm tube})$ in which the L/R_{el} ratio of the inter-electrode gap value to their radius describes the electric field nonuniformity inside the discharge tube whereas the $L/R_{\rm tube}$ ratio characterizes the diffusion loss of electrons on the discharge tube walls. It has been found that the breakdown curves for different electrode radius values and a fixed gap L intersect at such value of the gas pressure that corresponds to the location of the inflection point of the breakdown curve for a uniform electric field.

NW1 33 Vibrational Kinetics of Electronically Excited States in H_2 Discharges GIANPIERO COLONNA, LUCIA DANIELA PIETANZA, *Plasmi Lab CNR Nanotec Bari* ROBERTO CELIBERTO, *DICATECh, Polytechnic of Bari and Plasmi Lab CNR Nanotec Bari* MARIO CAPITELLI, ANNARITA LARICCHIUTA, *Plasmi Lab CNR Nanotec Bari* The StS model of hydrogen plasmas has been improved, including in the kinetic scheme the vibrational levels of the relevant electronically excited singlet terms, responsible for the H_2 spectral emission, and correspondingly the vibrationally-resolved cross sections and the radiative decay coefficients, describing the de-excitation dynamics. Also the triplet state evolution resulting from the competition between the collisional quenching and the predissociation mechanism, both leading to dissociation, is considered. This model has been applied to repetitively pulsed nanosecond discharges. The evolution of the molecule, including excited states, atomic hydrogen and ionic species molar fractions is shown during the pulse and compared with the results obtained neglecting either the vibrational kinetics or the collisional quenching of excited singlets. The differences are discussed in the light of the modifications of the shape of the eedf and ground state vibrational distribution function, emphasizing the role of quenching at the pressures considered in the simulation. The model could be validated in low-pressure regimes, missing experimental results in high-pressure discharges.

NW1 34 Second harmonic wave generation in ununiform microwave plasma by metamaterial effect AKINORI IWAI, YOSHIHIRO NAKAMURA, *Kyoto University* OSAMU SAKAI, *The University of Shiga Prefecture* THE UNIVERSITY OF SHIGA PREFECTURE TEAM, KYOTO UNIVERSITY TEAM We performed the monitoring of plasma parameters and intensity of second harmonic (SH) wave in the composite of microwave overdense plasma and the metamaterial under the various conditions; input power, gas pressure and the position of the detection. Plasma has been dealt with the nonlinear optical material because of the inherent nonlinearity based on the complex motion of particles in plasma. Moreover, generation of ions from plasma is important for many industrial processes. However, electron density n_e provides the threshold frequency ω_{pe} and the electromagnetic (EM) wave cannot penetrate into rich-n_e plasma when the frequency is under ω_{pe}; plasma permittivity (ε) becomes negative. We introduced double-split-ring resonators (DSRRs), one of metamaterials, which macroscopically have negative permeability (μ) by the magnetic resonance, and canceled the negative ε. Our previous report [1] included the rough results about SH wave generation and n_e in terms of the monitoring positions. In this report, we show the relation between the propagation of the input wave (2.45 GHz), SH wave and parameters of generated plasma in detail, and clarify the microscopic effect of DSRRs.

[1] A. Iwai, Y. Nakamura, and O. Sakai, Phys. Rev. E **92**, 033105 (2015).

NW1 35 DC discharge sustained by repetitive nanosecond pulses in nitrogen with a single pair of electrodes* KEISUKE TAKASHIMA, TOSHIRO KANEKO, *Department of Electronic Engineering, Tohoku University* To enhance the nitrogen molecule dissociation reactions with the oxygen and water, a nanosecond pulse (NS) sustained DC discharge in nitrogen is experimentally studied in a coaxially arranged discharge cell with a single pair of exposed electrodes. The DC discharge current is sustained by repetitive nanosecond pulse discharge which propagates along the discharge cell and the DC current follows the ionized channel produced by the NS discharge. The total discharge coupling power reaches nearly 1kW power loading to moderated pressure nitrogen flow with relatively low voltage across the gap. The discharge characterization on the repetitive NS discharge and the NS sustained DC discharge with the gas mixture will also be presented.

*This work is supported by JSPS KAKENHI Grant-in-Aid for Young Scientists (A) Grant Number 17H04817.

NW1 36 Variations in Plasma Parameters in the Plume of a DC Plasma Source Near a Substrate* SOPHIA GERSHMAN, YEVGENY RAITSES, *Princeton Plasma Physics Laboratory* A three-electrode dc plasma source was constructed and operated in Ar at pressures of 2–10 torr. The plasma source consists of two cylindrical electrodes with dimensions in the mm range and 1 mm inter-electrode distance, and a third, biased electrode/substrate, positioned in front of the cathode or in front of the anode opening. Optical and electrical measurements show that plasma at the substrate has a higher temperature (12–14 eV) on the anode side than on the cathode side (4–7 eV). The biased electrode offers flexibility in controlling plasma-surface interactions by extracting electrons of various energies from the discharge. This electrode exploits the non-local electron kinetics to control plasma properties in the plume from the discharge near the surface of the electrode/substrate.

*This work was supported by the U.S. Department of Energy (DOE), Office of Science, Fusion Energy Sciences (FES) under DOE Contract No. DE-AC02-09CH11466.

NW1 37 Effects of pulse modulation on the density distributions of ions and molecules in Ar/H_2 inductively coupled plasma* KWON-SANG SEO, DONG-HYUN KIM, HO-JUN LEE, *Electrical and Computer engineering, Pusan National University* Pulse modulation operation of inductively coupled plasma(ICP) and microwave plasma is an effective method for controlling plasma chemistry through active utilization of afterglow process and temporal variation of electron energy. In this work, effects of power pulsing on the neutrals and ions chemistry in Ar/H_2 ICP are investigated using 2D fluid simulations. Driving frequency of ICP was 13.56 MHz and pulse frequency was varied from 10 to 20 kHz. The effects of pulse frequency, duty cycle, and gas mixture ratios have been analyzed comprehensively. For comparison with continuous mode, time average power of pulse mode was set equal to the continuous mode. The atomic ions such as Ar^+ and H^+, generated dominantly by electron impact reaction, increase only during the plasma on time. However, dimer and trimer ions like H_2^+, H_3^+ increase rapidly during plasma off time because important generation channels of these ions are gas phase reaction including charge transfer reaction. During the off period, ion flux toward chamber surface remains very low level due to rapid cooling of elections. These variations profoundly affect the density distributions of dimer and trimer ions.

*Effects of pulse modulation on the density distributions of ions and molecules in Ar/H_2 inductively coupled plasma.

NW1 38 Experimental characterization of a magnetized ICP source used as the first stage of an Inductive Double-stage HALL Thruster (ID-HALL)* FREDDY GABORIAU, LOIC DUBOIS, ALEXANDRE GUGLIELMI, LAURENT LIARD, JEAN-PIERRE BOEUF, *LAPLACE* GREPHE TEAM The new generation of all-electric propulsion satellites requires multimode thrusters able to provide high thrust for orbit transfer and high specific impulse for satellite station keeping. In conventional Hall thruster, the same electric field provides electron energy for ionization and controls the ion acceleration, thus thrust and specific impulse are closely linked. The concept of double-stage Hall thruster (DSHT), where ionization is separated and controlled independently from ion acceleration, allows separating thrust and specific impulse. This concept raises fundamental questions and the challenge is to obtain a high degree of ionization in the first stage and an efficient extraction of the ions from the ionization region to the acceleration stage. To address this issue, a new concept of DSHT called ID-HALL is proposed. The ionization stage is a cylindrical ICP source with a closed magnetic circuit (confining the plasma and reducing ion losses) and is magnetically connected to the standard Hall acceleration stage. Results regarding the efficiency of the ICP source with and without the closed magnetic circuit will be presented and discussed based on the determination of the electron density and the electron temperature using single and double probes.

*This work is supported by the french government space agency CNES, Toulouse (France).

NW1 39 Experimental investigation on the E to H transition in a dual frequency inductively coupled plasma (2 MHz/13.56 MHz) JU-HO KIM, HO-WON LEE, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University, South Korea* A transition from a capacitive mode to an inductive mode is investigated in a dual frequency inductively coupled plasma. The frequency powers of 13.56 MHz and 2 MHz are applied to the two antennas, respectively. The plasma density is measured using RF compensated Langmuir probe. The density jump due to the transition with increasing power is measured at 13.56 MHz and 2 MHz respectively, and compared to dual frequency operation. The characteristics in the transition can be explained by the absorbed power and the lost power with respect to the plasma density and driving frequency difference.

NW1 40 Comparison of power transfer efficiency and plasma parameters of series and parallel antennas in inductively coupled plasmas TAE-WOO KIM, HYUN-JU KANG, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* When the capacitive coupling between the antenna and plasma is large, it is hard to make the high density plasma due to the large ion energy losses inductively coupled plasma. Therefore, the parallel antenna structure is commonly used in plasma processing chamber to reduce the capacitive coupling. However, when a parallel antenna is used, the power transfer efficiency from the antenna to the plasma is low because the primary inductance (antenna inductance) is lower than that of the series antenna and the mutual inductance is also lower in the transformer model. In this study, the power transfer efficiency and the plasma parameters were measured to investigate the effects of the series and parallel antennas on the plasma. To compare the series and parallel antennas, both antennas were made of copper tubes of the same length and thickness. The experiment shows that the parallel antenna has good ionization efficiency and the series antenna has good power transfer efficiency as expected from the model.

NW1 41 The effect of a remote plasma generator on a direct inductively coupled plasma SE-YEOL PAEK, KYUNG-HYUN KIM, HO-WON LEE, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* The electron energy distribution functions (EEDFs) were measured in a planar inductively coupled plasmas (ICP) with a remote plasma generator (RPG) using Langmuir probes. RF power frequencies of the ICP and the RPG were 13.56 MHz and 2 MHz, respectively. While the gas pressure and the argon flow rate are varied, the plasma density is changed little with the RPG, however, the electron temperature is changed remarkably. The change in electron temperature is not monotonically decreased and the pressure condition of minimum electron temperature is moved. This phenomenon can be explained by the changes in EEDFs depending on the RPG.

NW1 42 Experimental investigation of rf bias power on the plasma density and electron heating in an inductively coupled plasma HO-WON LEE, JU-HO KIM, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* Plasma densities are measured with rf bias powers at an inductively coupled plasma (ICP) using rf compensated Langmuir probe. When the ICP power is fixed, the plasma density has a maximum at a specific rf bias power. The rf bias power having maximum plasma density varies with ICP powers. This seem to be related to discharge mode transition (electron heating mode and ion acceleration mode) according to rf bias powers. These modes are determined by the power balance depending on rf bias voltages. Since the rf bias voltage decreases with ICP power, the bias power having the maximum density is shifted. This shows that electron heating and generation can be controlled by rf bias power..

NW1 43 Electron energy distribution function measurement in a CO_2/Ar inductively coupled plasma KYUNG-HYUN KIM, KWAN-YONG KIM, CHIN-WOOK CHUNG, *Department of electrical engineering, Hanyang university* Electron energy distribution functions (EEDFs) in CO_2/Ar mixed plasma were measured at various fractions of the argon. Electron density increases with ratio of the argon. Electron temperature has maximum values in a pure CO_2 plasma. On the other hand, the electron temperature increases with the argon ratio in CO_2/Ar plasma. EEDF becomes from Maxwellian to non-Maxwellian by increasing pressure and decreasing the Ar ratio because Maxwellization of EEDF is determined by the electron-electron collision frequency and electron energy relaxation frequency. Unusual phenomenon occurs at intermediate pressure, 50 mTorr. It is the EEDF of the pure CO_2 plasma is closer to the Maxwellian than those of the CO_2/Ar plasma with a small proportion of Ar. This result seems to be effect of superelastic collisions determined by vibration-vibration (V-V) exchange and vibration-translation (V-T) relaxation.

NW1 44 Calibration of Two-photon absorption laser induced fluorescence measurements of atomic oxygen density in a capacitively coupled plasma system JIM CONWAY, MILES TURNER, *National Centre for Plasma Science & Technology, Dublin City University, Ireland* STEPHEN DANIELS, *National Centre for Plasma Science & Technology, Dublin City University* Two-photon Absorption Laser Induced Fluorescence (TALIF) is frequently used to measure atomic oxygen number density [O] in plasma. Calibration is usually performed using a Xenon based TALIF scheme. Photolysis of O_2 gas can also be used to calibrate the TALIF system. Photolysis greatly simplifies calibration as the same species (O) is probed during calibration and measurement. Also, any high intensity saturation effects encountered are identical in both cases allowing laser intensity to be increased outside the TALIF quadratic laser power region without affecting calibration reliability. This produces stronger TALIF signals. In our approach O_2 photo-dissociation and two-photon excitation of the resulting [O] are performed by the same laser pulse. Photolysis generated [O] is spatially non-uniform and time varying, so spatial and temporal correction factors are required to allow valid comparison with any plasma generated [O]. The correction factors can be found using a rate equation model. A capacitive plasma system is calibrated using both Xe and O_2 photolysis approach and [O] values measured for various settings on the system. The [O] results are compared to validate the O_2 photolysis technique.

NW1 45 Electron density and electron temperature measurements for repetitive nanosecond pulsed discharges using Thomson scattering* JARED MILES, STEVEN ADAMS, *Air Force Research Laboratory* JAMES HORNEF, CHUNQI JIANG, *Old Dominion University* AFRL TEAM, ODU PLASMA AND PULSED POWER LAB TEAM Measurements of electron temperature and electron density in repetitive nanosecond pulsed plasmas provide key insight to the properties and kinetics of non-equilibrium plasmas. This work applies non-invasive Thomson scattering to spatially and temporally resolved measurements of electron temperature and electron density in repetitively pulsed plasmas in ambient air and inert gas flows. Plasmas were generated by a pin-to-pin electrode system driven by 12 ns, 6-10 kV pulses at a repetition rate up to 300 kHz. A <1 mm in width He/O_2 plasma jet produced by a tubular electrode configuration and powered by 140 ns kilovolt pulses at 10 Hz was also used for the study. The dependence of the plasma properties including the electron temperature, electron density and gas temperature on pulse duration, pulse rise time, and gas composition are discussed here.

*Work is supported by the Air Force Research Lab Summer Faculty Fellowship Program and in part by the Air Force Office of Scientific Research under Award Number FA9550-17-1-0257.

NW1 46 Investigation of the flow rate effect on the plasma parameters by using miniaturized plasma diagnostic device in the remote plasma HYUN-DONG EO, JIN-YOUG KIM, CHIN-WOOK CHUNG, *Department of electrical engineering, Hanyang university* Miniaturized plasma diagnostic device was developed for installing near the remote plasma source because there is a little space for the monitoring system. Miniaturized plasma diagnostic device can be used like a gauge without additional connection with measuring instrument and computer. Miniaturized plasma diagnostic device used the floating harmonic method that used for obtaining plasma parameters such as electron temperature and ion density. Experiments were conducted to measure plasma parameters in the remote source with wall probe. As increasing the flow rate of the remote source, the increase of the ion density and electron temperature is observed by using our device.

NW1 47 Picosecond TALIF to quantify collisional quenching of laser-excited states in atmospheric pressure plasmas* SANDRA SCHROETER, JEROME BREDIN, KARI NIEMI, TIMO GANS, DEBORAH O'CONNELL, *York Plasma Insitute, University of York* The accurate quantification of reactive oxygen species produced in atmospheric pressure plasmas is of great interest in various applications, such as surface modification and biomedicine. A technique commonly used for the detection of atomic ground state species is Two-photon Absorption Laser Induced Fluorescence (TALIF). For the measurement of absolute species densities, this technique relies on the knowledge of the laser-excited state lifetime. However, typical TALIF systems operate on timescales of nanoseconds, which is in the same order as the lifetimes of the laser-excited states due to their enhanced collisional de-excitation (quenching) at atmospheric pressure. Therefore, the effective lifetimes have to be calculated using quenching coefficients from the literature and an estimate of the gas mixture, which is particularly challenging taking into account complex gas mixing with ambient air in the plasma effluent region. In this work, we present measurements of the decay rates of the laser-excited states in the effluent of an rf atmospheric pressure plasma operated in helium with small molecular admixtures using TALIF with a sub-nanosecond temporal resolution. Quenching coefficients of the excited state $O(3p\,^3P_{1,2,0})$ with various gases such as Ar, O_2, N_2, CO_2, and H_2O are measured and compared to literature values. The active measurement of decay rates is used to map the gas entrainment of ambient air into the plasma effluent region.

*Supported by UK EPSRC (EP/K018388/1, EP/H003797/1).

NW1 48 Passive Optical Emission Spectroscopy for the electric field measurements in DC and RF sheaths in IShTAR* ANA KOSTIC, *Ghent University; Max-Planck-Institut für Plasmaphysik* KRISTEL CROMBE, *Ghent University; LPP-ERM-KMS, TEC partner* RUDOLPHE D'INCA, JONATHAN JACQUOT, ROMAN OCHOUKOV, *Max-Planck-Institut für Plasmaphysik* ANTON NIKIFOROV, *Ghent University* JEAN-MARIE NOTERDAEME, *Ghent University; Max-Planck-Institut für Plasmaphysik* ISHTAR TEAM TEAM Direct, non-intrusive measurements of the electric field are essential for the progress in understanding the RF sheath physics. This is especially true in the case of the ICRF antenna - plasma edge interaction in fusion devices. Here the rectification of the RF fields near the plasma-facing components of the antenna leads to the development of DC electric fields. These DC fields accelerate the ions from the plasma towards the antenna's plasma-facing components thereby enhancing physical sputtering and release of impurities. IShTAR is a device dedicated to the investigation of the edge plasma-antenna interactions in tokamak edge-like conditions. It is equipped with a helicon plasma source and a single-strap ICRF antenna. We present here our initial approach to measure the electric fields - the passive optical emission spectroscopy concentrating on the changes of the He-I spectral line profiles introduced with the external electrical field, i.e. the Stark effect. To be able to fully control the operating parameters, at the first stage of the study the measurements are conducted on a simple electrode installed in the IShTAR plasma source at the centre of the plasma column. At the second stage of the study, the measurements are preformed in the vicinity of the ICRF antenna of IShTAR. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

*This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under Grant Agreement No 633053.

NW1 49 Electron temperature of an RF discharge in argon up to atmospheric pressure ANTOINE DUROCHER-JEAN, *Departement de physique, Universite de Montreal, Montreal, Canada* JEAN-SEBASTIEN BOISVERT, *Institut national de la recherche scientifique, Varenne, Canada* JOELLE MARGOT, LUC STAFFORD, *Departement de physique, Universite de Montreal, Montreal, Canada* A cold argon plasma is generated inside a dielectric tube (inner diameter of 2 mm) using two long linear electrodes painted on diametrically opposed sides of the tube. The optical emission spectra from Ar 4p-to-4s transitions were compared to the predictions of a collisional-radiative model using the electron temperature T_e (assuming a Maxwellian EEDF) and the Ar $1s_2$ level number density as the only adjustable parameters. T_e was deduced from the best fit between measured and simulated line emission intensities. At 760 Torr, the best fit is obtained for T_e=1.28 eV. When the power density increases from 4.2 to 7.0 W cm^{-3}, T_e remains constant while n_e (estimated from electrical measurements) increases from 3.7 to 8.8 × 10^{11} cm^{-3}. In this range of power density, the discharge remains in the Ω mode with a maximum of the light emission (dominated by a continuum in the UV-VIS range) at the center of the tube. By reducing the pressure to 90 Torr, the best fit is achieved for a higher T_e of 1.50 eV. On the other hand, the power density, n_e and the continuum intensity decrease with decreasing pressure. In contrast with a helium discharge in the same range of discharge current, the argon discharge does not switch to the γ mode.

NW1 50 Measurement of effective electron collision frequency in low pressure RF plasmas by the microwave resonator* VIKTOR ZHELTUKHIN,† *Retired* ILDAR GAFAROV, *Scientific-Development Company Renarisorb Ltd* VADIM GALEEV, ANASTASIA GOLYAEVA, ALEXANDER TOVSTOPYAT, *M.F. Stelmach's Scientific Institute POLUS* Results of the experimental studying of effective electron collision frequency ν_c with heavy particles in RF plasmas at pressure range from 13.3 up to 332.5 Pa is presented. The plasmas were created in a cylindrical quartz tubes from 20 up 40 mm by the diameter. The discharge power was varying from 100 up to 1000 W. RF frequency f_{RF} was varying from 1 up to 18 MHz. Diagnostics of the discharge was carried out by microwave resonators in UHF and microwave ranges. The probing signal frequency was varying from 5 to 12 GHz. The wave of $\mathring{A}_{oso}$ type was excited in a cylindrical resonator. Average collision frequency and electron density n_e in the discharge gap were measured. The collision frequency varies almost linearly in full range of f_{RF} varying. The collision frequency exceeds 10^{10} s^{-1} when p >150–180 Pa. Electron density n_e is increased depending on voltage by linear low at low-power mode, and is increased approximately by square-law at high current mode.

*The work was funded by RFBR&TAS, project No. 15-41-02672.
†68, K. Narx St., Kazan 420015, Russia.

NW1 51 A monolithic cavity-enhanced absorption spectrometer for NO2 detection in the ppb concentration levels A. LOZANO FONTALVO, A. M. JUÁREZ, *Instituto de Ciencias Físicas, Universidad Nacional Autónoma de México.* THOMAS SIEGEL, *ASE Optics Europe.* In the past decade, many diagnostic techniques have been developed to detect and quantify the concentration of pollutants such a NOx. Among them, Incoherent broad-band cavity-enhanced absorption spectroscopy (IBBCEAS) which employs a LED as a radiation source and an optical cavity to enhance the absorption of the LED light is one of the simplest. The relatively wide spectrum of wavelengths provided by LEDs allows this technique to simultaneously detect many pollutants such as NO_2 and NO_3 with enhanced sensitivity. In this work we report the development of a spectrometer which implements an IBBCEAS set-up which uses a LED centered at 634 nm, for the detection of NO_2. The optimal averaging acquisition time for this instrument, as evaluated using Allan variance, is found to be of 500 s. For this acquisition time, the smallest detectable absorption is 1.01×10^{-9} cm^{-1}, which corresponds to a detection limit of 3.36 ppb. The monolithic design presented in this work, does not require the alignment of mirrors, making it very practical and easy to handle. This compact and inexpensive instrument is a promising tool for monitoring air quality among many other applications including the generation of traces in plasmas and molecular biological processes.

NW1 52 Modelling of capacitive coupled RF discharge in wide pressure range* VIKTOR ZHELTUKHIN,† *Retired* VIOLETTA CHEBAKOVA,‡ *Kazan Federal University* A model of capacitive coupled RF discharge in argon at both atmospheri and low pressures between two parallel plate is described. Various approaches to simulate the RF discharge depending on pressure rates are used. A nonlocal approximation is used simulating the capacitive coupled RF discharge at low pressure. A local approximation considering both dimers and molecular ions is used for simulating the discharge at high pressure. Results are in agree with experimental data.

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‡18, Kremlevskaya St., Kazan 420008, Russia.

NW1 53 Modeling and Simulation of Rarefied RF Plasma Flow* VIKTOR ZHELTUKHIN,† *Retired* ALEXANDER SHEMAKHIN,‡ *Kazan Federal University* A hybrid mathematical model of the rarefied RF plasma flow in transition regime at Knudsen 0.03 < Kn < 3 for the carrier gas is described. The model based on both the statistical approach to the ground-state atom and the continuum model for electron, ion, and metastables. The results of plasma flow calculations are described. The upwarming effect on the bound of the plasma stream near the input is found in some mode. The effect is confirmed by comparison with experimental data.

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NW1 54 Simulation of low energy ion bombardment of alkane in low pressure RF plasmas* VIKTOR ZHELTUKHIN, *Retired* ALBINA AZANOVA, IGOR BORODAEV, AIDOGDY SHAKHYROV,† *Kazan National Research Technological University* Results of molecular dynamics simulation of low energy (up to 100 eV) ion bombardment of both crystalline and amorphous alkanes in low pressure RF plasmas are described. An united-atom model of alkane chains where each site represents a CH2 group or a CH3 end group is used. The covalent bond between adjacent sites is modeled by a Dreiding potential. The interaction between the sites in different chains, as well as between argon and alkane sites is described by a LJ potential. A classical molecular dynamics code LAMMPS is used.

*The work was funded by RFBR, according to the research Projects No. 15-41-0276, 16-31-00482.

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NW1 55 Comparison of Particle-in-Cell and Fluid Simulations on Ion Energy Distribution Function and Mobility in intermediate Pressure Capacitively Coupled Plasmas YOONHO LEE, SEHUN OH, JINSEOK KIM, HAEJUNE LEE, *Pusan National University* The variation of the ion energy and angle distribution functions in the capacitively coupled plasma is changing rapidly with the variation of gas pressure because of the increase of ion-neutral collisions with increasing gas pressure. In general, it has been accepted that fluid models work well in high pressure discharges where the drift-diffusion approximation is valid, while the non-local property of low pressure discharges can be analyzed correctly with a particle-in-cell (PIC) model. In this study, the mean ion velocity in the sheath is investigated for an intermediate gas pressure of a few Torr, which shows a significant discrepancy between the PIC results and the fluid results for different phases of an RF-cycle. In this regime, the discrepancy between two models is mainly caused by the ion momentum equation in the sheath regions due to the intrinsic properties of fluid equations. Especially, we found out that the mobility obtained from the PIC model and the mobility used in the fluid model are significantly different. We are suggesting an improved model in order to estimate the ion mobility reflecting the results of the PIC model. Finally, the results of the improved fluid model that utilizes this mobility are demonstrated and compared with the PIC simulation results.

NW1 56 Simulation of mist-containing low-temperature plasma in atmospheric-pressure helium* FUMIYOSHI TOCHIKUBO, FUMIYA MURAYAMA, SATOSHI UCHIDA, *Tokyo Metropolitan University* Plasma-liquid interaction is a hot topic in the application of atmospheric-pressure plasma (APP). Using mist will be the efficient method to increase the effective area for plasma-liquid interaction. When mist is introduced to the APP, each droplet will be charged negatively, therefore, reductive reaction is expected at the surface of droplet. The evaporation of mist will change the gas composition. The aim of this work is to clarify the physics of mist-containing APP by numerical modeling. First, the evaporation process of the droplet was modeled by the conservation laws of mass and energy for droplets and surrounding gases. Second, the dust plasma in atmospheric-pressure helium was calculated by fluid model with heat equation for gas as parameters of particle's diameter and concentration. The APP modeled in this work is dc glow discharge and dielectric barrier discharge. The charge of particle with diameter of 1 μm in APP ranges from 10^3 to 10^4 of elementary charge. At particle concentration greater than 10^7 cm^{-3}, the particles influences the plasma structure as a strong loss term for electrons and ions although the charge density itself is much lower than the plasma density. The simulation with mist is ongoing by combining the above two models.

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NW1 57 Effect of Flow Shear and Curvature on Plasma Instabilities* J WALLS, A PATEL, O JOHNSON, B FELBER, *Bowie State University, MD* S SEN, *William & Mary, National Institute of Aerospace, VA and Bowie State University, MD* M GOLDSTEIN, *NASA-Goddard, University of Maryland Baltimore Country, MD, and University of Colorado, CO* We study the effect of inhomogeneous flow on low-frequency instabilities and turbulence. The inhomogeneous flow includes both flow shear and flow curvature. The effect of flow curvature (second radial derivative of flow) is shown to have significant effect in controlling the turbulence level contrary to the usual prediction that flow shear (first radial derivative of flow) alone controls the turbulence level. The detail result of this simulation will be reported.

*This work is supported by the DOE Grant DE-SC0016397.

NW1 58 Grid-based kinetic simulations of ladder climbing by electron plasma waves* KENTARO HARA, *Texas A&M University* IDO BARTH, *Department of Astrophysical Sciences, Princeton University* EREZ KAMINSKI, *Birmingham-Southern College* ILYA DODIN, NATHANIEL FISCH, *Department of Astrophysical Sciences, Princeton University* Wave-plasma interactions have been well studied in collisionless plasmas and the grid-based kinetic model is a promising tool to accurately model phase space structures in plasmas. It was recently proposed by Barth *et al.* [1] that the energy of plasma waves can be moved up and down the spectrum using chirped modulations of plasma parameters. Depending on whether the wave spectrum is discrete (bounded plasma) or continuous (boundless plasma), this phenomenon is called ladder climbing or autoresonant acceleration of plasmons. In this talk, ladder climbing of electron plasma waves is investigated by applying a chirped external electric field using a fully nonlinear Vlasov-Poisson simulation of collisionless bounded plasma. It is shown that, in agreement with the basic theory, plasmons survive substantial transformations of the spectrum, i.e., Landau-Zener transitions, and are destroyed only when their wave numbers become large enough to trigger Landau damping.

*The work was supported by the U.S. NNSA SSAA Program through DOE Research Grant No. DE-NA0002948, the U.S. DTRA Grant No. HDTRA1-11- 1-0037, and the U.S. DOE through Contract No. DE-AC02-09CH11466.

[1] Barth *et al.*, Phys. Rev. Lett. **115**, 075001 (2015).

NW1 59 SPECT3D, Imaging and Spectral Analysis Package IGOR GOLOVKIN, JOSEPH MACFARLANE, VIKTORIYA GOLOVKINA, *Prism Computational Sciences* SPECT3D is a collisional-radiative spectral analysis package designed to compute detailed emission, absorption, or x-ray scattering spectra, filtered images, XRD signals, and other synthetic diagnostics. The spectra and images are computed for virtual detectors by post-processing the results of hydrodynamics simulations in 1D, 2D, and 3D geometries. SPECT3D can account for a variety of instrumental response effects so that direct comparisons between simulations and experimental measurements can be made. We will present new features of SPECT3D and highlight their application to the analysis of HEDP experiments. We will discuss a newly implemented capability to simulate scattering signatures from realistic experimental configurations, which include the influence of plasma non-uniformities and collecting scattered x-rays from a range of angles. Other improvements include support for a wider range of hydrodynamics codes and improved lineshape models for spectral lines from neutral atoms.

NW1 60 Effect of surface protrusion on plasma sheath properties in DC microdischarges* YANGYANG FU, PENG ZHANG, JOHN VERBONCOEUR, ANDREW CHRISTLIEB, *Michigan State University* PLASMA THEORY AND SIMULATION GROUP TEAM The electric field enhancement due to the presence of cathode surface protrusion is investigated in the atmospheric DC microdischarges with the goal of identifying the plasma sheath properties. The electric field enhancement of a semi-ellipsoidal protrusion is examined by adjusting the semi-major axis, a, and the semi-minor axis, b, of the ellipsoid. It is found that the cathode electric field enhancement depends strongly (weakly) on the aspect ratio (size) of the protrusion, when it is much smaller than the discharge gap distance. In particular, when the protrusion is spherical ($a = b$), the cathode electric field enhancement in vacuum, as well as inside the plasma, are found to be almost constant against the radius of the hemispherical protrusion. The corresponding plasma sheath thickness is also nearly a constant with different radius. When the protrusion is ellipsoidal ($a \neq b$), the electric field enhancement decreases and the sheath thickness increases, when the semi-minor axis b increases. However, the ratio of the cathode electric field in vacuum to that in the steady-state plasma is found to be nearly a constant. The results indicate that effects of surface protrusions on plasma sheath properties are correlated with their vacuum electric field distributions.

*The work was supported by the Department of Energy Plasma Science Center Grant DE-SC0001939.

NW1 61 The PLASIMO plasma modeling framework WOUTER GRAEF, DIANA MIHAILOVA, JAN VAN DIJK, GERRIT KROESEN, *Eindhoven University of Technology* PLASIMO is a plasma modeling framework that has been under continuous development in the EPG plasma group at the Applied Physics Department of Eindhoven University of Technology since the 1990s. Since its initial form, aimed at modeling Inductively Coupled Plasmas and Cascaded Arcs, it has gained much functionality catering to a plethora of plasma applications: LTE and non-LTE, steady state and transient, flowing and non-flowing, with and without space charges, and from zero dimensional Global Models to full 3D simulations. The platform, which is developed in C++, is characterized by a high degree of modularization, offers a user friendly Graphical User Interface, and is available on multiple platforms, including Linux, Windows, and macOS. We present assorted applications where PLASIMO has been successfully employed, concentrating on recently added capabilities of the platform and their use cases.

NW1 62 Simulation of a laser triggered vacuum switch* ANDREW FIERRO, CHRISTOPHER MOORE, WENG CHOW, LAURA BIEDERMANN, MATTHEW HOPKINS, *Sandia National Laboratories* Laser triggered vacuum switches (LTVS) use input laser energy to inject electrons, ions, and neutral material from a trigger target into an electrically stressed vacuum gap. The reliability, power, and high output power of lasers make the LTVS an appealing approach for low-jitter, high voltage switching applications. Modeling of a LTVS allows for optimization of both laser and trigger material parameters for efficient operation. Essential to the laser triggering process is the injection of charged and neutral species at the trigger material surface. As such, a material supply model has been developed and is a function of the input laser intensity, wavelength, and pulse shape. This material model serves as an input flux boundary condition for into a particle-in-cell (PIC), direct simulation Monte Carlo (DSMC) code which simulates plasma growth and gap closure. Two hemispherical electrodes with a gap distance of 500 micron are simulated with the laser propagating axially towards the cathode through a small hole in the anode. An applied potential of several kV establishes an electrostatic potential. Plasma formation for various laser energies and wavelengths are compared to establish general trends of the LTVS.

*Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE NNSA under Contract DE-NA0003525.

NW1 63 The Design of Raw Data Management System for Plasma Surface Reaction Modeling and Simulation JUNHYOUNG PARK, WON-SEOK CHANG, MI-YOUNG SONG, *National Fusion Research Institute* PLASMA FUNDAMENTAL TECHNOLOGY RESEARCH TEAM Plasma-based process technology is an important technology in semiconductor manufacturing process. By using the data of the surface reaction utilizing the plasma chemical reaction, it is possible to control the gas mixing ratio or the discharge variable necessary for the process and the material characteristics. In this method, the yield of semiconductors can be improved and highly precise processing becomes possible. In order to apply it not only to the semiconductor field but also to various industries and research, experiments on multiple plasma surface reactions are being conducted. In particular, physical and chemical analysis is necessary to solve the problem of process yield and improvement of yield of semiconductor process. However, basic plasma surface reaction data necessary for related simulation and modeling is not managed / provided efficiently. DCPP of the NFRI provides research data such as plasma collision and thermodynamics to industries and researchers as a data center that collects and disseminates experimental / research data on plasma physical properties. We are trying to design a system that can manage and provide related experiments and research data to provide data related to plasma surface reactions via database systems in the data center.

NW1 64 Modification of adhesion ability of carbon fabrics for composite materials* VIKTOR ZHELTUKHIN,[†] *Retired* AIDAR GARIFULLIN, MARS SHAEKHOF,[‡] *Kazan National Research Technological University* Modification of the carbon fabrics by RF capacitive coupled discharge at low pressure (13–130 Pa) is studied. The plasma treatment leads to increasing of surfaces area of the carbon fibers, to creation of active radicals, and to decreasing of wetting angle. The cumulative impact of these factors leads to increasing of wettability of technical textiles. It is established that carbonyl and hydroxyl functional groups are formed after RF plasma treating. Regulation of carbon fabrics properties by RF capacitive coupled plasma allow us to create composite materials which have strength values by 15–20% higher than control samples.

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NW1 65 Regulation of properties of hollow fiber membranes by low-temperature plasma* VIKTOR ZHELTUKHIN, *Retired* RUSTAM IBRAGIMOV,† *Kazan National Research Technological University* Hollow fiber polysulfone membranes with an internal selective layer were treated by low-pressure air RF plasmas. It is found that oxygen-containing functional groups on the internal surface of membranes is formed due to RF plasma action. The mean arithmetic deviation of the roughness profile (Ra) and the height of the irregularities (Rz) of the surface microrelief the membrane is decreased. The pore diameter in the membrane is equalized. The cumulative influence of these factors leads to significant increasing of hydrophilization of the selective membrane layer.

*The work was funded by RFBR in association with Tatarstan Academy of Sciences, Project No. 15-41-02672.
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NW1 66 Analysis of mechanical and physical properties of metal cutting tools processed by low pressure RF plasmas* VIKTOR ZHELTUKHIN, *Retired* ALBERT KHUBATKHUZIN,† *Kazan National Research Technological University* Physical and mechanical characteristics of metal cutting tools treated by capacitive coupled RF plasma are investigated. Topography, roughness, hardness, wear resistance, modulus of elasticity, elastic recovery coefficient and the thickness of the modified layer in a single instrument was studied. Gas saturation (carbonizing) of surface layers of metals and alloys at a depth of 1 micron during to 40 minutes processing was obtained, resulting in an increase of strength properties, durability and lifetime of the products. Research of wear resistance was carried out by experiments on field trials of "Northwest trunk pipelines". Results are showed that lifetime increases in the range from 140 up to 230%. The complex approach to the study of surfaces with the use of methods to measure.

*The work was funded by RFBR in association with Tatarstan Academy of Sciences, Project No. 15-41-02672.
†68, K. Marx St., Kazan 420015, Russia.

NW1 67 Numerical study of atomic layer precision control for SiO2 etching ZHANG SAIQIAN, DAI ZHONGLING, WANG YOUNIAN, *School of Physics and Optoelectronic Engineering, Dalian University of Technology* In semiconductor fabrication industry, the application of 3D structures makes profile, damage and selectivity control more difficult. Atomic layer etching (ALE) becomes a potential way to achieve high precision control of etching. In ALE, cyclic passivation and removal of the passivated layer are performed and the self-limiting nature guarantees the 1ML/cycle in ideal case. But throughput issue arises from purge step limits the application, many study try to achieve the ALE or ALE-like precision control with less time or equipment costs by compromising the precision. In this study, a multi-dimensional model is built to simulate the SiO2 etching in fluorocarbon plasmas. First, global and sheath model are used to get energetic particle fluxes. Then particles are traced in the trench model and finally a surface Monte Carlo method is used to consider surface reactions. Results show that by cyclic control of high and low ion energies, better precision control is achieved compared to conventional etching, even without alternating the feed gas. But non-ideal etching like micro-trenching, sidewall slope exists. Control of ion energy distribution and duty ratio of energy modulation can be used to optimize the profile and selectivity control.

NW1 68 Control of radical and ion production in chlorine plasma* DAVID CARON, *West Virginia University* COSTEL BILOIU, *Applied Materials - Varian Semiconductor Equipment* EARL SCIME, *West Virginia University* Parameters controlling the fluxes of chlorine radicals and ions in a directional reactive ion etch device are presented. The etching device consists of an inductively coupled plasma source and ion extraction optics. Optical emission spectra of chlorine plasma were investigated over 200–800 nm spectral range and characteristic spectral features of Cl lines and Cl_2 bands identified. Optical actinometry with trace amounts of rare gases was employed in order to obtain parameters of interest. From the ratios of integrated line/band emissions and rare gas line intensities, the absolute density of Cl and Cl_2 species were inferred. Dependencies of radical and ion production on gas flow rate, pressure, and input RF power were obtained. These results allow for fine tuning of Cl_2 plasma in directional reactive ion etching.

*Work supported by NSF under GOALI Grant Number 1617880.

NW1 69 3D Feature Profile Simulation of Cyclic Fluorocarbon Atomic Layer Etching Process SANGHEON SONG, *Lam Research Corporation* YEOUNG GEUN YOOK, HAE SUNG YOU, YEON HO IM, *Chonbuk National University* Recently, a great deal of attention has been placed on atomic layer etching (ALE) processes as semiconductor features continue to shrink below 10 nm. ALE is a technique for removing a few monolayers of material using sequential reaction steps that are self-limiting. A cyclic plasma-enhanced fluorocarbon ALE process has attracted much interest for its selective etching and atomic-level control. A Lam Research Corp. etch system enabling this process has been qualified for manufacturing of logic devices. To build upon Lam's achievement it requires more feasibility studies for wide applications on various 3D nanoscale patterns. To address this issue, we've performed 3D topography simulations coupled with a realistic surface reaction model for the cyclic fluorocarbon ALE process for silicon oxide. In this work, 3D topography simulations were performed for a multiple 3D-level-set-based moving algorithm, a 3D ballistic transport of chemical species coupled with zero-D bulk plasma simulation, and a surface reaction module. This work can lead to a better understanding of the cyclic fluorocarbon ALE process and its application to next-generation sub-10 nm devices.

NW1 70 Efficiency technique of in-situ dry cleaning process in etch chamber YUSIN KIM, JUNGHWAN UM, *Samsung Electronics Co.* In order to achieve the same process results in one chamber, it is very important to keep the wall condition constant at all times. Therefore the in-situ dry clean process (ISD) is performed after each wafer is processed. End point detection (EPD) technique, which is traditionally used in the process, is applied to vary the ISD time according to the chamber wall conditions. As a result of applying the appropriate EPD algorithm according to the type of ISD gas, the minute change of the chamber is observed with the EPD time of ISD. In addition, plasma simulations were performed to find the ISD condition to minimize the surface damage caused by the plasma generated during ISD. As a result of applying the conditions derived from the simulation and the EPD technique, process defects due to particles falling off the surface are reduced.

NW1 71 New developments in Nb surface modification using a cylindrically symmetric capacitive discharge* JEREMY PESHL, *Old Dominion University* MILKA NIKOLIC, *University of San Francisco* JANARDAN UPADHYAY, *Los Alamos National Laboratory* SVETOZAR POPOVIC, ALEXANDER GODUNOV, LEPOSAVA VUSKOVIC, *Old Dominion University* We performed the ion-assisted reactive ion etching of a single cell Superconducting Radio Frequency (SRF) cavity made of pure Niobium (Nb) in a capacitive rf Ar/Cl_2 discharge with cylindrical symmetry. The first rf test of a plasma etched SRF cavity at cryogenic temperature has shown no field emission, which did not increase even after multiple chemical cleanings and testing. The absence of field emission is interpreted by the effect of plasma wake field on the SRF cavity walls. In addition, we will present effects of the etching parameters on the surface roughness of cavity grade Nb. Efforts on the development of plasma diagnostics employing different line intensity ratio techniques to evaluate emission spectroscopy data and deduct plasma parameters will be presented. A comparison of the spectral data from an Ar plasma and an Ar/Cl_2 plasma show an interesting influence of DC bias – a necessary parameter in the etching of the larger surface electrode – on the electronegative characteristics of the Ar/Cl_2 plasma.

*Supported by the DOE under Grant No. DE-SC0014397.

NW1 72 Simulation of Large Area Inductively Coupled Plasmas using CF_4/O_2 Gas for Dry Etching of a Flat Panel Display GEONWOO PARK, MIN YOUNG HUR, *Pusan National University* CHANGROK CHOI, HOONBAE KIM, *LG Display* M. J. KUSHNER, *University of Michigan* HAE JUNE LEE, *Pusan National University* As the demand for larger area display increases, the plasma uniformity is required in a chamber size of 2200 mm by 2500 mm (the 8th generation) or larger. The fluid simulation of a large area inductively coupled plasma (ICP) source is presented for the investigation of etch profiles and for the analysis of uniformity control. The plasma is produced by three by three ICP sources for the 8th generation flat panel display. The substrate is also biased with an RF source of 13.56 MHz in order to get high etching rate. Hybrid Plasma Equipment Model (HPEM) code is used for the simulation of CF_4/O_2 gas mixture, and the results are compared with experimental measurement of etch profiles. The generation and the transport of each species are analyzed for the variation of the input power and the bias voltage. Finally, the ratio of ion fluxes to neutral fluxes is compared with the etching profiles obtained by experiment.

NW1 73 Designing microscale gas discharges to enhance thermionic energy conversion JOHN HAASE, DAVID GO, *University of Notre Dame* Thermionic energy converters (TECs) are devices that convert heat directly to electricity via thermionic emission. In a TEC, a hot cathode emits electrons that are then collected by a cold anode, and when passed through a load, produces electrical work. However, the emitted electrons can build-up between the electrodes, retarding the current. Two strategies to combat the build-up negative space charge are to reduce the interelectrode gap, preferably to the micron-scale, or to introduce a positive space charge, a plasma. Previously [1], we showed that microscale inert gas plasmas could perform this role, and enhance thermionic emission, under steady state conditions. However, because energy must be injected to ignite the inert gap plasma, a microplasma-enhanced TEC device must be operated in a pulsed mode in order to achieve net power generation. In this work, we use the plasma modeling software Zapdos [2] to model an inert gas (argon) microplasma-enhanced TEC. We explore the effect of various system parameters on the net power produced by these TECs, and optimize the system parameters to maximize power output.

[1] J. R. Haase and D. B. Go, J. Phys. D: Appl. Phys. **49**, 55206 (2016).
[2] A. D. Lindsay, D. B. Graves, and S. C. Shannon, J. Phys. D: Appl. Phys. **49**, 235204 (2016).

NW1 74 The Role of Vibrational Energy on the Catalytic Production of Ammonia in Non-Equilibrium Atmospheric-Pressure Plasma* FRANCISCO HERRERA, PAUL RUMBACH, PATRICK BARBOUN, JONGSIK KIM, JASON HICKS, DAVID GO, *University of Notre Dame* Plasma-catalytic nitrogen fixation to produce ammonia from nitrogen and hydrogen feedstock has been investigated as a potential alternative to the conventional Haber-Bosch process because it can be operated under less extreme conditions and potentially more energy efficiently. However, the fundamental mechanisms behind this process are not fully understood. In this work, we use optical emission spectroscopy (OES), which is a non-invasive technique for estimating relative relevant parameters of the plasma, to correlate plasma behavior with measured nitrogen conversion in a plasma-catalytic reactor. Using OES, we have performed several measurements of nitrogen-hydrogen atmospheric pressure dielectric barrier discharges (DBD) at different controlled operational conditions. We extract the vibrational and rotational temperatures of the DBD by comparing our spectroscopic measurements with a modelled optical emission. We find that the vibrational temperature is strongly dependent on the gas composition and power, and we correlate this behavior to measurements of nitrogen conversion using the same DBDs in conjunction with oxide-supported metal catalysts.

*This work was supported by the Office of Energy under Award Number DE-FOA-0001569.

NW1 75 Effect of Radio Frequency Waves on Plasma Instabilities & Turbulences* J MELENDEZ, I DUROJAIYE, K TRIVEDI, E NTI, *Bowie State University, MD* S SEN, *William & Mary, National Institute of Aerospace, VA and Bowie State University, MD* We study the effect of Radio Frequency Waves on low-frequency instabilities and turbulences. No ponderomotive force induced flow generation is considered. In spite of this the effect of RF waves is shown to have significant effect in controlling the turbulence level contrary to the usual prediction that ponderomotive force induced flow shear (first radial derivative of flow) alone controls the turbulence level. This has a crucial role in the fusion energy generation.

*This work is supported by the DOE Grant DE-SC0016397.

NW1 76 PFC Abatement Using Microwave plasma source with annular-shaped slot antenna at sub-torr pressure* SEUNGIL PARK, SUNG-YOUNG YOON, CHANGHO YI, SEONG BONG KIM,† SEUNGMIN RYU, JAESUNG OH, SUK JAE YOO, *National Fusion Research Institute* We present a feasibility study of a microwave plasma source with annular-shaped slot antenna for abatement of PFCs gas from semiconductor manufacturing

WEDNESDAY AFTERNOON \ NW1

processes. According to the company's requirements, the concept of this plasma source could be designed to have a cylinder-shaped metal reactor with quartz tube, an annular-ring resonator with an annular-shaped slot antenna, and a microwave components. In order to investigate the concept of this source, the prototype device was designed to maximize an electric field in the reactor for the breakdown using the 3D finite element method (FEM) code and fabricated with the inner diameter of 100 mm. The argon plasma was generated in the pressure range from 0.04 to 4 torr by the commercial magnetron with the power of 1 kW and the frequency of 2.45 GHz. The plasma properties such as the argon metastable density and the gas temperature have been measured by a tunable diode laser absorption spectroscopy (TDLAS). By using this plasma, destruction and removal efficiencies (DRE) over 90% for CF4 were achieved with the additive gases by a quadrupole mass spectrometry (QMS). In this paper, the initial design and the preliminary experimental results of a new microwave plasma source would be discussed.

*This work was supported by R&D Program of 'Plasma Advanced Technology for Agriculture and Food (Plasma Farming)' through the National Fusion Research Institute of Korea (NFRI) funded by the Government funds.

†Corresponding author.

NW1 77 Visible light effects in plasma plume ignition LANLAN NIE, *Huazhong University of Science and Technology* The breakdown delay time of a closed plasma plume excited by a high-voltage pulse is investigated. The visible monochromatic light of 404, 532, and 662 nm wavelength and narrow-waveband light at a central wavelength of 400, 430, 450, 470, 500, 530, 570, 610, and 630 nm are used to pre-ionize the gas. It is found that the breakdown delay time decreases when the visible light illuminates the discharge tube. The light is most effective when it is applied at the position near the high-voltage electrode. The effect of visible light is found to inversely relate to the wavelength, manifested by the longer breakdown delay times for longer wavelengths. With increasing the frequency and the pulse width of the voltage, the visible light shortens the delay time more effectively. These observations can be explained by the visible light-enhanced generation of free electrons before the ignition. The proposed mechanisms of free-electron generation are the optically stimulated exoelectron emission from the inner surface of the discharge tube wall and the vibrational excitation of nitrogen molecules. The effects of visible light weaken with the addition of oxygen as a result of electron affinity to oxygen.

NW1 78 Instabilities in fluid simulations of ExB plasmas GERJAN HAGELAAR, SARAH SADOUNI, *LAPLACE, CNRS and University of Toulouse* The operation of magnetized low-temperature plasma devices such as Hall thrusters and magnetrons involves various types of plasma instabilities, generally causing anomalous electron transport across the magnetic field lines. This paper demonstrates that fluid models of these plasma devices, when solved properly in the 2D plane perpendicular to the magnetic field lines, intrinsically produce some of such plasma instabilities and anomalous transport, whose behavior may or may not be realistic, depending on the configuration and conditions. Results are shown from a self-consistent fluid code developed at LAPLACE based on standard fluid equations for continuity, momentum and energy of (partially) magnetized electrons and ions, for different simple ExB plasma configurations. These results are compared with PIC simulations, checked against a linear instability analysis and interpreted in terms of basic instability types known in the literature.

NW1 79 Nanosecond-pulsed DBD in atmospheric air and methane-nitrogen mixtures* DANIL DOBRYNIN, CHONG LIU, ALEXANDER FRIDMAN, *Drexel University* Dielectric barrier discharges (DBDs) are non-equilibrium low-temperature discharges. Uniform dielectric barrier discharges have many potentially transformative industrial applications, including uniform thin-film deposition, surface modification of polymers, sterilization of biological samples, treatment of living tissues and cells for their advantages of low gas temperature, moderate power density, uniform energy distribution, controllability of chemical composition and so on. Uniform DBDs are traditionally generated at special conditions (e.g., low pressure, rare gases), and in atmospheric air are of filamentary nature. Recent developments in pulsed power generation technology allowed controllable application of fast-rising short (nanosecond) high voltage pulses for generation of pulsed discharges. In our preliminary studies we have been able to perform fast imaging of the discharge development on nanosecond time scales in atmospheric air, and show transition of DBD from filamentary to uniform mode. We show that the discharge uniformity may be achieved in the case of strong overvoltage (provided by fast rise times), when anode-directed streamers are formed. Here we present our results on fast ICCD imaging of DBD in atmospheric air and methane-nitrogen mixtures for uniformity analysis, as well as temperature and local electric filed measurements using OES.

*This work is funded by the NSF/DOE Partnership in Basic Plasma Science and Engineering (DOE Grant DE-SC0016492).

NW1 80 Computational Modeling of Microwave Interactions with Self-consistent Plasma ROCHAN UPADHYAY, *Esgee Technologies Inc.* LAXMINARAYAN RAJA, *The University of Texa at Austin* Computational modeling of microwave plasma needs to resolve several observed phenomena occurring in microwave-sustained plasmas. This is a challenging task as while the microwave wavelength is of the order of millimeters or more, several phenomena of microwave plasma interactions occur in the range of micrometers or less. Examples include the skin effect in over-dense plasma, the "epsilon-zero" resonance and subsequent enhanced power deposition at the critical density interface, the structure of SPP (Surface Plasmon Polaritons) in plasma dielectric interfaces, Microwave-(sheath)Voltage Plasma (MVP) etc. We will briefly present several examples of computational simulations, using a self-consistent fluid plasma model coupled with full field electromagnetic simulations for industrial scale plasma reactors for which the above physical mechanisms are the main processes for the creation and sustenance of the plasma for material processing applications. We will focus on two problems, namely discharges sustained by surface wave propagation (SWP) along plasma- dielectric interface (SPP) and by SWP along the plasma-sheath interface (MVP). Computational simulations illustrate the differences between the two types of discharges and the dependence of plasma on external parameters.

NW1 81 Discharge modes in oil submerged spark gap with gas injection KUNPENG WANG, XIN TANG, DAVID STAACK,* *Texas A&M University* Electrical discharge in submerged spark gap with gas injection was experimentally studied with two different commonly used electric circuits. One RC circuit with constant voltage and a double spark gap circuit were used. The charging time of the RC circuit before breakdown was comparable with the bubble residence time in the spark gap, while the second circuit with double spark gap finished charging and discharging on the second capacitor two orders of magnitude faster than the bubble rising time. Consequently, bubble dynamics are relatively independent of the applied electric field if we use the second circuit. Three different discharge mechanisms were proposed. The first breakdown mechanism is believed to happen in the gas phase only when the entire spark gap was enclosed in a gas bubble. Breakdown occurs first on the electrode tips where a stronger electric field is present. The second discharge mechanism is initiated by contaminates in the liquid. When contaminates get charged from one electrode and move in the electric field towards the second electrode, breakdown happens during this process. The third discharge mechanism we proposed is due to the interactions between either charged bubbles or charged bubbles and electrode.

*Dr. David Staack is the corresponding author of this publication.

NW1 82 Nonlinear ECDI and anomalous transport in E×B discharges* SALOMON JANHUNEN, ANDREI SMOLYAKOV, OLEKSANDR CHAPURIN, *Univ of Saskatchewan* DMYTRO SYDORENKO, *Univ of Alberta* IGOR KAGANOVICH, YEVGENI RAITSES, *Princeton Univ / PPPL* Cross-field anomalous transport is an important feature affecting the operation and performance of $E \times B$ discharges. Instabilities excited by $E \times B$ flow cause anomalous current to develop, characterized in the nonlinear regime by a large amplitude coherent wave driven by the energy input from the unstable cyclotron resonances. A persistent train of soliton-like waves characterized by the fundamental cyclotron wavelength appears in ion density. Simultaneously, there is inverse energy cascade toward long wavelength which is manifested by the formation of the long wavelength envelope of the wave train. It is shown that the long wavelength part of the turbulent spectrum provides a dominant contribution to anomalous electron transport. We present results from 1D3V and 2D3V PIC simulations, with finite boundaries in 2D. Influence of inhomogeneities in density and magnetic field on the development of the $E \times B$ drift cyclotron instability is investigated, as well as the non-linear mechanisms behind the coherent structures and their interactions.

*Work supported by Westgrid Compute/Calcul Canada, NSERC Canada, and US AFOSR Grant FA9550-15-1-0226.

NW1 83 A UV Lamp Power Supply and Method for Improved UV Lamp Performance in Vertical Applications BRETT SKINNER, DARRIN LEONHARDT, CHARLES WOOD, *Heraeus Noblelight America* UV Lamps are ubiquitous in the curing of industrial coatings, inks, and adhesives. Most applications, such as printing, require the lamps to be oriented horizontally. Yet many applications like optical fiber require the lamp to be vertical. First-generation, ferroresonant power supplies, with their aggressive ripple, allowed lamps to be operated both vertically and horizontally. Then, DC power supplies were implemented into horizontal applications due to their numerous advantages over their precursor: higher efficiency, lighter weight, lower risk of slot arcing and magnetron internal moding, and more. However, the lack of turbulence in the plasma yielded an unsymmetrical distribution of the bulb fill along the bulb length in additive bulbs when not horizontal. As a result, significantly decreased overall UV output occurs along with increased peak temperatures that can reduce the lifetime of the bulb, precluding the use of DC power supplies in vertical applications. In order to study the effects that the waveform driving both engines in the power supply has on the bulb, a special power supply was built which allows all aspects of the waveform to be controlled: duty cycle, fall time, rise time, frequency, phase delay, and peak current. Years of testing these parameters have produced a waveform that provides the benefits of both DC and ferroresonant power supplies without the drawbacks inherent in both. This paper examines the impact that each waveform parameter has on vertical bulb performance.

NW1 84 Conversion of Lignin to Valuable Compounds Induced by Discharge Plasma at Gas/Liquid Interface* SHIGENORI TAKAHASHI, *Nagoya University* MASAMI BITO, *J-Chemical, Inc.* MASAHIRO TOKUDA, *Sugiyama Chemical & Industry Lab.* WAHYU DIONO, NORIHARU TAKADA, HIDEKI KANDA, MOTONOBU GOTO, *Nagoya University* This work focused on the pulsed discharge plasma as oxidation process of lignin obtained from wood. The pulsed discharge plasma is a low-cost process because the process is performed under normal conditions. The objective of this study is to convert lignin into value-added products induced by pulsed discharge plasma, such as vanillin. Lignin that used as a starting material was extracted from the wood powder of Japanese cedar by dissolving it in sodium hydroxide solution. Experiments were conducted using a batch type reactor and DC pulsed discharge plasma power supply unit. The DC pulsed voltages at 10–18 kV were introduced on the extracted lignin solution via the copper electrode under atmospheric pressure air or argon. The electrode was set at distance of 2 mm from the lignin solution surface. The products from the conversion of lignin in the aqueous solution were identified and quantified by HPLC. The results showed that the production of vanillin during discharge in air environment was larger than in argon environment due to expectedly abundant reactive oxygen species formation. However, the production of vanillin after discharge in argon environment was more rapid than in air environment following by the low molecular weight of lignin derived compounds.

*Conversion of Lignin to Valuable Compounds Induced by Discharge Plasma at Gas/Liquid Interface.

NW1 85 Controlling the Directional Motion of Water Droplet on Polymer by Titled Nanopillar Fabrication by rf PECVD* LAN PHAN,[†] MYOUNG-WOON MOON,[‡] *Korea institute of science and technology* In this work, we used plasma in radio frequency plasma enhance chemical vapor deposition (rf PECVD) to fabricate the slanted nanopillars with diameter around tens of nm on PET polymer, control the angle of tilted nanopillars on the substrate using Faraday cage. The top-view and cross-view of SEM show that the mushroom-liked nanopillar formation was created thank to the etching of O2 gas plasma under the shading effect of metal cluster come from electrode and metallic cage under the bombardment of ion. The XRD result with high density of metallic oxide from stainless steel confirms the assumption. A directional motion of water droplet on nanopillar layer show the specific function of this nanostructure. The work could activate lots of potential applications by its high surface ratio and other specific purposes such as control the cell motion, directional water condense, and so.

*Controlling the directional motion of water droplet on polymer by titled nanopillar fabrication by rf PECVD.

[†]Division of Nano & Information Technology, KIST School, Korea University of Science and Technology, Seoul 02792, Republic of Korea.

[‡]Division of Nano & Information Technology, KIST School, Korea University of Science and Technology, Seoul 02792, Republic of Korea.

NW1 86 Vibrational excitation of CO_2 by Nanosecond Repetitively Pulsed sparks ERWAN PANNIER, VALENTIN BAILLARD, CHRISTOPHE LAUX, *CentraleSupelec* CO_2 can be used as a feedstock for synthetic gas (syngas) production, both for ground and space (Mars settlement) applications. In these processes, CO_2 splitting into CO and O_2 is the most energy consuming step. Previous studies have shown that nonequilibrium plasma discharges can perform this dissociation with a maximum energy efficiency through the excitation of vibrational levels of CO_2 in a process known as the ladder-climbing mechanism. In this work, we investigate the contribution of vibrational excitation in CO_2 dissociation with nanosecond repetitively pulsed discharges (NRP). In particular, we investigate the potential of the high repetition frequency (10–20 kHz) to yield a synergetic effect that increases the vibrational temperature over several pulses. The vibrational excitation of CO_2 is measured with time-resolved, phase-locked IR emission spectroscopy in the 4.2 um asymmetric stretch band. The vibrational temperature is inferred from a comparison with non-equilibrium spectra calculated with the CDSD-HITEMP database. Populations of vibrationally excited states are compared with results from a 0D vibrationally-specific kinetic code to study the synergetic effect of successive discharges.

NW1 87 Growth and characterization of graphene films by halogen based plasma etching of ^{6}H-SiC* CHARTER STINESPRING, ANDREW GRAVES, SAURABH CHAUDHARI, SRIKANTH RAGHAVAN, *Department of Chemical Engineering, West Virginia University* The synthesis of graphene has received considerable attention due to its remarkable properties. We have developed a novel plasma based method for producing graphene films on silicon carbide. Specifically, CF_4 and Cl_2 based inductively coupled-reactive ion etching is used to selectively remove Si from the near surface layers of ^{6}H-SiC(0001). The graphene film is then formed by rapid thermal annealing of this carbon rich layer at 970°C under atmospheric pressure argon or ultrahigh vacuum conditions. The composition, structure, and thickness of these films have been characterized using x-ray photoelectron spectroscopy, reflection high energy electron diffraction, Raman spectroscopy, and atomic force microscopy. The results indicate that the films are epitaxial with a thermally stable defects which buckle the graphene surface. The plasma parameters, most notably the bias voltage, are used to control the number of graphene layers. This allows reproducible synthesis of one, two, and three layer graphene films. Metal-graphene-metal structures have been characterized using simple current-voltage measurements. These exhibit Schottky type behavior. We believe this may be due to semiconducting behavior produced by the observed defect structures.

*US Department of Energy.

NW1 88 Argon Plasma Generated By High Repetition Rate, Nanosecond Pulses: Time-Resolved Measurements of Voltage, Current, and Electron Number Density* VLADLEN PODOLSKY, ANDREI KHOMENKO, SERGEY MACHERET, *Purdue University* Weakly ionized plasmas sustained by high repetition rate nanosecond pulses have shown promise for a number of applications due to the low power budget, efficient ionization, and enhanced production of excited species. To study the dynamics of such plasmas, time-resolved probe measurements of voltage and current as well as microwave interferometry measurements of the spatially-averaged electron density were conducted in argon at a pressure of several Torr and parallel-plate electrode spacing of several centimeters. From the measured electron density decay between the pulses, the recombination rate coefficients were inferred. This provided an insight into the recombination mechanisms. In particular, the dimer ions Ar^{2+} were found to be dominant, so the recombination was primarily dissociative. The relaxation time of the electron temperature was also determined and found to be much shorter than the recombination time. Since the time interval between the pulses is much longer than the pulse duration and the electron temperature relaxation time, most of the time the plasma has a relatively high electron density but low electron temperature and hence low Johnson-Nyquist noise. Such plasmas could thus be useful in radio-frequency electronics.

*This work was supported in part by the National Science Foundation under Grant ECCS-1619547 and in part by the Lockheed Martin Aeronautics Company.

SESSION PW2: LXCat DISCUSSION
Wednesday Evening, 8 November 2017
Room: Duquesne at 19:00
Larry Viehland, Chatham University, presiding

Contributed Papers

19:00

PW2 1 LXCat Discussion LARRY VIEHLAND, *Chatham College* LXCat (www.lxcat.net) is an open-access, web-based platform for storing, exchanging, and manipulating data needed for the electron and ion components in cold, non-equilibrium plasma. The LXCat session, Wednesday evening from 7 to 9 pm, is organized to facilitate the discussion of the future of the LXCat database. Everyone with interest in LXCat is encouraged to attend this GEC2017 event. At GEC2016, about 60 people were present and the discussion was lively. A couple of people prepared short presentations, but it was an informal event (i.e., no abstracts, etc).

SESSION QR1: MAGNETICALLY ENHANCED PLASMAS I
Thursday Morning, 9 November 2017
Room: Salon D at 8:00
Pascal Chabert, LPP Ecole Polytechnique, presiding

Contributed Papers

8:00
QR1 1 The role of recycling in pulsed sputtering magnetrons JON TOMAS GUDMUNDSSON, *University of Iceland, Reykjavik, Iceland and Department of Space and Plasma Physics, KTH-Royal Institute of Technology, Stockholm, Sweden* DANIEL LUNDIN, *LPGP, UMR 8578 CNRS, Université Paris-Sud, Orsay Cedex, France* MICHAEL A. RAADU, NILS BRENNING, *Department of Space and Plasma Physics, KTH-Royal Institute of Technology, Stockholm, Sweden* In high power impulse magnetron sputtering (HiPIMS), high power is applied to the magnetron target (cathode) in unipolar pulses at low duty cycle. This results in a high plasma density (electron density) and a high ionization fraction of the sputtered material. The time-dependent plasma discharge ionization region model (IRM) allows us to explore the temporal variation of the various parameters of the discharge process. Here we use the model to explore both non-reactive and reactive discharges. For high currents the discharge with Al target develops almost pure self-sputter recycling, while the discharge with Ti target exhibits close to a 50/50 combination of self-sputter recycling and working gas-recycling [1]. For a reactive operation we find that when the discharge is operated in the metal mode Ar^+ and Ti^+-ions contribute most significantly (roughly equal amounts) to the discharge current while in the poisoned mode the Ar^+-ions contribute almost solely to the discharge current [2]. In the metal mode self-sputter recycling dominates and in the poisoned mode working gas recycling dominates.

[1]C. Huo *et al.*, J. Phys. D: Appl. Phys. (submitted 2017).
[2]J. T. Gudmundsson *et al.*, Plasma Sources Sci. Technol. **25**, 065004 (2016).

8:15
QR1 2 Pressure dependence of Ar_2^+, $ArTi^+$, and Ti_2^+ dimer formation in a magnetron sputtering discharge* MARTIN CADA, *Institute of Physics, Academy of Science of the Czech Republic, Na Slovance 2, 18221 Prague 8, Czech Republic* RAINER HIPPLER, *Institut für Physik, Ernst-Moritz-Arndt-Universität Greifswald, Felix-Hausdor-Str. 6, D-17487 Greifswald, Germany* VITEZSLAV STRANAK, *University of South Bohemia, Faculty of Science, Branisovska 31, 37005 Ceske Budejovice, Czech Republic* ZDENEK HUBICKA, *Institute of Physics, Academy of Science of the Czech Republic, Na Slovance 2, 18221 Prague 8, Czech Republic* CHRISTIANE HELM, *Institut für Physik, Ernst-Moritz-Arndt-Universität Greifswald, Felix-Hausdor-Str. 6, D-17487 Greifswald, Germany* Formation of Ar^+ and Ti^+ monomer and of Ar_2^+, $ArTi^+$, and Ti_2^+ dimer ions in a magnetron sputtering discharge with a Ti cathode and in an argon atmosphere was investigated by means of energy-resolved mass spectrometry. Energy spectra of Ar^+ and Ti^+ ions show distinct features which are related to the specific formation processes taking place in the plasma region and during ion bombardment of the Ti cathode. Our observations proved that low-energy Ar^+ ions are produced inside the plasma region. Ti^+ ions originate from sputtering events. The measured energy distribution of titanium ions does not follow Thompson's formula, however. At the lowest gas pressure the measured energy distribution can be modelled by a shifted Maxwellian distribution. Formation of Ar_2^+, $ArTi^+$, and Ti_2^+ dimer ions show pronounced pressure dependencies which are attributed to various formation and loss processes.

*The work was partly supported by Projects 15-00863S and 16-14024S of the Czech Science Foundation, by the Project TF03000025 of the Technology Agency of the Czech Republic and by the German Academic Exchange Service (DAAD).

8:30
QR1 3 Low-frequency ionization oscillations due to azimuthally rotating spokes in cross-field configurations KENTARO HARA, *Texas A&M University* REI KAWASHIMA, *University of Tokyo* Rotating spokes are self-organizing coherent structures observed in magnetron discharge, Penning discharge, and Hall effect thrusters. The unique feature about the rotating spokes is that the oscillations are in the kHz range, i.e., low frequency compared to the electron dynamics due to the E×B drift. This indicates that the rotating spokes are ionization oscillations due to interaction between neutral atoms, ions, and electrons. A two-dimensional (axial-azimuthal) hybrid kinetic-fluid model is used to model the discharge plasma in a Hall effect thruster. It has been reported that the potential solver assuming a drift-diffusion approximation with the current balance equation introduces an ill-conditioned matrix, which is difficult to solve. A pseudo-time stepping method in which the diffusion equation is solved in a time-advanced fashion enables stable calculation of the potential solver. The low-frequency rotating spokes obtained from the hybrid simulation show qualitative agreement with published experimental data. The local dispersion relation of gradient drift waves indicates that the instability occurs in the downstream of the discharge plasma, and the simulation results agree with the phase velocity obtained from theory.

8:45
QR1 4 Plasma Diagnostics in Reactive High Power Impulse Magnetron Sputtering System ZDENEK HUBICKA, JIRI OLEJNICEK, MARTIN CADA, *Institute of Physics Czech Academy of Sciences Na Slovance 2 Prague 8, Czech Republic* PETRA KSIROVA, *Institute of Physics Czech Academy of Sciences Na Slovance 2 Prague 8* STEPAN KMENT, *Palacky University, RCPTM, 17. listopadu 12, 771 46 Olomouc, Czech Republic* DEPARTMENT OF LOW-TEMPERATURE PLASMA TEAM, RCPTM TEAM Plasma parameters in the reactive pulsed magnetron (R-HIPIMS) were investigated during films deposition. Parameters of Ar^+H_2S and Ar^+O_2 pulsed plasma were investigated by the emission spectroscopy, Langmuir probe, RF ion flux and impedance probes. Ionized fraction of sputtered particles and deposition rate were measured by the modified QCM with a magnetic filter and biased electrode. Different modes of reactive deposition process were found and described by physical model. This R-HIPIMS system was used for the deposition of semiconducting oxide and sulphide thin films. These semiconducting films were optimized for applications in solar water splitting solar cells. Oxide thin films such as Fe_2O_3 and TiO_2 films were deposited on FTO glass and Pt coated silicon substrates by R-HIPIMS in Ar^+O_2 gas mixture using target made of Fe and Ti, respectively. Photoelectrochemical performance of these films was investigated for various conditions and postdeposition annealing. Sulphide semiconductor FeS_2 films were deposited by R-HIPIMS in gas mixture of Ar^+H_2S and pure Fe target. Photoelectrochemical properties of these films were examined in dependence

on plasma parameters and postdeposition annealing in H_2S low pressure plasma.

9:00

QR1 5 Magnetic diagnosis of the plasma behavior in a dc non-transferred plasma torch* VIDHI GOYAL,† GANESH RAVI, *Institute for Plasma Research, Bhat, Gandhinagar-382428 India* In the present work, the dynamical behavior of the thermal plasma inside a dc non-transferred plasma torch is studied using magnetic probe diagnostics. The studies are performed using an indigenous plasma torch (TVG-25) where garlands of miniature magnetic probes have been incorporated inside the anode cooling channel in both axial and azimuthal directions to capture the plasma fluctuations. Experiments have been performed for a wide range of gas flow rates (20 to 60 l pm) and currents (70–120 A) in the presence of a strong axial external magnetic field (100 to 500 G) at atmospheric pressure with nitrogen as working gas. The arc root shunting and rotational phenomena have been captured by the probes and results show higher stagnation time of arc root for low magnetic field which decreases with increasing magnetic field. A clear shift of rotational frequency is also visible with higher discharge current showing effect of current density on the arc root motion, in agreement with results obtained using fast imaging diagnostics. Diagonally opposite magnetic probes show phase delay above a threshold, signifying constricted profile of arc current inside anode material.

*Affiliated to HBNI.

†I am a PhD student and about to finish within a year. I am very keen to attend this conference because it will provide a great platform for my further research.

9:15

QR1 6 Outer Ring-Shaped Magnetized Plasma by RF and HiPIMS Source HOSSAIN MD. AMZAD, YASUNORI OHTSU, *Graduate School of Science and Engineering, Saga University* We have proposed a magnetized outer ring-shaped plasma sputtering source with a concentrically monopole arrangement of magnets with each gap of R =5 mm for specific target area utilization by radio frequency (RF) and high power impulse magnetron sputtering (HiPIMS). The three setups are investigated such as with a center magnet with case (a): magnet arrangement with three circles, case (b): magnet arrangement with two circles, and case (c): magnet arrangement with one circle from the point of view of specific outer area target utilization. In the experiments, Ar gas of 12.0 [Pa], RF power of 50100 [W] at 13.56 [MHz] for RF discharge and Ar gas of 12.0 [Pa], target voltage of 6001000 [V] at 2.5 [kHz] and pulse width of 20 μs for HiPIMS source are used to produce the plasma. 2D magnetic field map shows that the magnetic flux density in component transverse to the target surface has a peak density the exterior circle of magnet arrangement for all setups. Ring-shaped plasma in the specific target outer area is observed for both RF and HiPIMS discharge where the transverse component of magnetic flux is sufficiently high and its diameter depends on a number of magnets on the circles. The experimental results are summarized based on the radial profile of ion saturation current, plasma density and the typical discharges between RF and HiPIMS source.

SESSION QR2: DIAGNOSTICS III
Thursday Morning, 9 November 2017
Room: Duquesne at 8:00
Vladimir Demidov, West Virginia University, presiding

Contributed Papers

8:00

QR2 1 Simultaneous Diagnostic of Temperature Distribution and Electric Field induced in Dielectric Target by Atmospheric Pressure Plasma Jet ELMAR SLIKBOER, *LPP, CNRS, Ecole Polytechnique, UPMC, Université Paris-Saclay, 91128 Palaiseau, France* ENRIC GARCIA-CAUREL, *LPICM, CNRS, Ecole Polytechnique, Université Paris-Saclay, 91128 Palaiseau, France* ANA SOBOTA, *Department of Applied Physics, EPG, Eindhoven University of Technology, The Netherlands* OLIVIER GUAITELLA, *LPP, CNRS, Ecole Polytechnique, UPMC, Université Paris-Saclay, 91128 Palaiseau, France* A polarimetric technique is used to image the complete Mueller matrix of a sample under plasma exposure. This allows for the spatial investigation of the optical properties modified by the plasma. In particular, the birefringence of a BSO crystal contains information about the induced electric field in the target and hence about charges deposited on its surface by the discharge. Additional new findings shows simultaneously a secondary signal in the birefringence which is related to the temperature distribution. This is due to temperature induced strain. Measuring the temperature profile in the target allows for the investigation of the amount of heat that is produced in the plasma jet and transferred to the target. The heat distribution on the surface is investigated for different gas mixtures of both feeding gas of the jet as for the controlled environment in which it is placed. Simultaneously, the spatial and temporal evolution of surface electric field and charge deposition profiles are obtained. This simultaneous diagnostic helps gaining better understanding of the plasma kinetics involved in the atmospheric pressure plasma jet with different gas mixtures.

8:15

QR2 2 Ultrafast Laser Diagnostics to Interrogate High Pressure, Highly Collisional Plasma Environments* EDWARD BARNAT, ANDREW FIERRO, *Sandia National Laboratories* The implementation and demonstration of laser-collision induced fluorescence (LCIF) generated in atmospheric pressure helium environments is presented in this communication. As collision times are observed to be fast ($\sim$10 ns), ultrashort pulse laser excitation ($<$100 fs) of the 2^3S to 3^3P (388.9 nm) is utilized to initiate the LCIF process. Both neutral induced and electron induced components of the LCIF are observed in helium afterglow plasma as the reduced electric field (E/N) is tuned from $<$0.1 Td to over 5 Td. Under the discharge conditions presented in this study (640 Torr He), the lower limit of electron density detection is $\sim 10^{12}$ e/cm^3. Spatial profiles of the 2^3S helium metastable and electrons are presented as functions of E/N to demonstrate the spatial resolving capabilities of the LCIF method.

*This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under Contracts DE-AC04-94SL85000 and DE-SC0001939.

Invited Papers

8:30

QR2 3 Electric Field Measurements in Nanosecond Pulse Discharges in Air over Solid and Liquid Dielectric Surfaces

IGOR ADAMOVICH, *Ohio State University*

Electric field in nanosecond pulse discharges in ambient air is measured by picosecond four-wave mixing, with absolute calibration by a known electrostatic field. The measurements are done in a discharge between two parallel cylinder electrodes covered by quartz tubes, and in a discharge between a razor edge high-voltage electrode and a plane grounded electrode covered by a quartz plate or by a layer of distilled water. In the positive polarity discharge between the parallel cylinders, peak electric field, 140 kV/cm, considerably exceeds DC breakdown threshold. In the negative polarity discharge between the razor blade and quartz surface, the field follows the applied voltage until "forward" breakdown occurs, after which the field in the plasma decays due to charge separation. When the applied voltage is reduced, the field reverses direction and increases again, until the "reverse" breakdown occurs, producing a secondary reduction in the field. Spatially resolved measurements show that the discharge develops as a surface ionization wave. Measurements of electric field vector components demonstrate that the vertical field in the wave peaks ahead of the horizontal field. Behind the wave, the vertical field remains low, while the horizontal field is gradually reduced. In the discharge over water surface, electric field is measured for both positive and negative pulse polarities, with durations of about 10 ns and about 100 ns, respectively. In the positive polarity pulse, breakdown threshold is 85 kV/cm, and no field reversal is detected during the voltage reduction. In the negative polarity pulse, breakdown occurs at 30 kV/cm, due to much longer pulse duration, and the field reverses direction when the voltage is reduced. After the pulse, the residual field over quartz and water surfaces decays on a microsecond time scale, due to surface charge neutralization by charge transport from the plasma. The results demonstrate considerable potential of the present technique for electric field measurements in atmospheric pressure discharges, providing quantitative insight into charge transport and plasma kinetics near plasma-liquid interface.

THURSDAY MORNING \ QR2

Contributed Papers

9:00

QR2 4 In-situ nanoparticle detection with Coherent Rayleigh-Brillouin Scattering* ALEXANDROS GERAKIS, *Princeton Plasma Physics Laboratory* MIKHAIL SHNEIDER, *Department of Mechanical & Aerospace Engineering, Princeton University* BRENTLEY C. STRATTON, YEVGENY RAITSES, *Princeton Plasma Physics Laboratory* We report on the development and application of a new laser diagnostic for the in situ detection of large molecules and nanoparticles. This four wave mixing diagnostic technique relies on the creation of an optical lattice in a medium due to the interaction between polarized particles and intense laser fields. This diagnostic was already successfully demonstrated in atomic and molecular gaseous environments, where the different gas polarizabilities and pressures were successfully measured. Finally, using this diagnostic technique, we demonstrate the first *in situ* measurement of nanoparticles with dimensions of few nanometers and number densities in the order of 10^{12} cm^{-3}, produced in an graphitic arc discharge [1].

*This work was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division.

[1] A. Gerakis, M. N. Shneider, and B. C. Stratton, Appl. Phys. Lett. **109**, 031112 (2016).

9:15

QR2 5 Remote sensing a low temperature plasma in the radio near field* SEAN KELLY, PATRICK MCNALLY, *Dublin City University* Plasma diagnosis is central to improving fault detection and control during semiconductor fabrication. Industrial scenarios however present relatively 'hostile' conditions detrimental to immersed probes. Probe contact with the plasma can be disruptive and negatively impact process replication, a key challenge in high volume manufacturing lines. Plasma diagnostics which are non-invasive and installation free (remote) are therefore particularly advantageous for modern industrial plasma scenarios. A novel diagnostic approach is proposed which intercepts the magnetic flux emanating from plasma currents in the vicinity of a view-port for a low pressure capacitively coupled plasma source. A calibrated near field magnetic loop antenna and a proprietary radio (spectrum analyzer) system is utilized to interrogate the low power signal levels in the radio part of the electromagnetic spectrum. Induced signal strength is found to correlate to the current measured using an in-line I-V probe. Frequency analysis reveals the signals rich harmonic content. Comparison of the relative harmonic amplitudes show resonance features associated with the series (geometric) plasma resonance. Corroboration via complimentary diagnostics (I-V, Hairpin and Langmuir probe) is performed in this context.

*Enterprise Ireland Project No. CF2014-4300.

SESSION QR3: COLLISIONS WITH ATOMS

Thursday Morning, 9 November 2017; Room: Oakmont Junior Ballroom at 8:00; Sandra Quintanilla, University of North Texas, presiding

Invited Papers

8:00

QR3 1 Free-free experiments: the search for dressed-atom effects*

N.L.S. MARTIN, *University of Kentucky*

The absorption or emission of radiation during the collision of charged particles with atoms and molecules is investigated in free-free experiments. Up to now almost all such experiments have been in agreement with a simple theory which assumes that the interaction of the radiation with the atom itself has no effect on the scattering process. Very recently the first experiments to observe the unambiguous breakdown of this assumption have been carried out in xenon by Morimoto, Kanya, and Yamanouchi [1]. An estimate of the dressing of the target by the radiation's electric field may be made in terms of the electric dipole polarizability α of the target. The effects in Xe ($\alpha = 28$ au) were extremely difficult to measure because they occur at very small scattering angles. We have begun to carry out electron-collision experiments for atomic processes which involve polarizabilities an order of magnitude larger than elastic scattering from Xe. Two such processes are elastic scattering from Potassium, and inelastic scattering into the first excited states of argon; both involve polarizabilities $\alpha \sim 300$ au. I will give a progress report on our experiments.

*This work was carried out by NLSM (supported by NSF Grant PHY-1607140), C. M. Weaver, B. N. Kim (University of Kentucky, and B. A. deHarak (supported by NSF Grant 1402899).

[1] Y. Morimoto, R. Kanya, and K. Yamanouchi, Phys. Rev. Lett. **115**, 123201 (2015).

Contributed Papers

8:30

QR3 2 Electron Impact Excitation of Xenon* DIRK LUGGENHOELSCHER, UWE CZARNETZKI, *Ruhr University (Bochum, Germany)* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University (Des Moines, Iowa, USA)* We have applied a novel experimental technique to measure cross sections for electron-impact excitation of the $5p^5 6s$ and $5p^5 6p$ states of xenon from its $5p^6$ ground state. This is a complex collision system, for which benchmarking of theory against experiment is needed. The experiment is performed using ultrashort current pulses released from an electrode by femtosecond laser pulses with 80 MHz repetition rate. In order to minimize space charge effects, only about 10^4 electrons are generated in each pulse. Electrons are accelerated by a homogeneous electric field to energies of typically 250 eV. The fluorescence light generated in collisions with Xe atoms at low pressure (Pa range) is imaged perpendicularly and provides a direct image of the energy-dependent excitation cross section. The calculations were carried out with a fully relativistic and parallelized version of the B-spline R-matrix code [1], using a 75-state close-coupling model [2] with the target structure obtained earlier [3].

*OZ and KB acknowledge support from the United States National Science Foundation.

[1] O. Zatsarinny, Comput. Phys. Commun. **174**, 273 (2006).
[2] O. Zatsarinny and K. Bartschat, J. Phys. B: At. Mol. Opt. Phys. **43**, 074031 (2010).
[3] O. Zatsarinny and K. Bartschat, Phys. Scr. T **134**, 014020 (2009).

8:45

QR3 3 B-spine R-matrix with pseudostates calculations for electron-impact excitation and ionization of magnesium* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* The B-spline R-matrix with Pseudo-States method [1,2] was employed to treat electron collisions with magnesium atoms. Predictions for elastic scattering, excitation, ionization, and ionization-excitation were obtained for all transitions between the lowest 25 states of Mg in the energy range from threshold to 100 eV. The accuracy of the results was checked by comparing with available experimental data and with results obtained in different approximations with increasing number of coupled states. The largest scattering model included 716 coupled states, most of which were pseudo-states that simulate the effect of the high-lying Rydberg continuum and, most importantly, the ionization continuum on the results for transitions between the discrete states of interest. Similar to our work on e-Be collisions [3], this effect is particularly strong at "intermediate" incident energies of a few times the ionization threshold. The dataset generated from the largest model is estimated to be accurate to within a few percent for the cross sections of relevance for plasma modelling.

*Work supported by the NSF under PHY-1403245, PHY-1520970, and XSEDE-090031.

[1] O. Zatsarinny, Comput. Phys. Commun. **174**, 273 (2006).
[2] O. Zatsarinny and K. Bartschat, J. Phys. B **46**, 112001 (2013).
[3] D. V. Fursa and I. Bray, J. Phys. B **49**, 235701 (2016).

Invited Papers

9:00

QR3 4 Double ionization of helium by electron and proton impact. A Generalized Sturmian Functions Approach
MARCELO AMBROSIO, *Kansas State University*

In this contribution we explore the double ionization of helium by fast electrons and protons. A first-Born framework is considered for the projectile-target interaction, while all the intra-target ones are considered to all orders. This reduces the number of active components from four particles to three, and the resulting three-body problem can be tackled with today's computational resources [1–3]. We apply the Generalized Sturmian Functions method to obtain the scattering wavefunction, and from its asymptotic part we extract the transition amplitudes. We present theoretical fully differential cross sections calculated for a wide variety of energy and momentum transfer regimes. A general good agreement is observed when they are compared with experimental data [4–7]. For electronic projectiles, for given momentum transfer values, higher order effects are appreciable in the measured cross sections, and some differences with first Born calculations are noticeable [5]. However, in the case of protonic projectiles we observe that a first Born treatment is enough to reproduce the features of the available experiments [6,7]. Analyzing the different energy and momentum transfer regimes, we are able to distinguish which collisional mechanisms are more preeminent in each regime [7]. This work was done in collaboration with Dr. Darío Mitnik, Prof. Lorenzo Ugo Ancarani, Dr. Gustavo Gasaneo, Antonio Gómez and Enzo Gaggioli.

[1] J. Berakdar *et al.*, Phys. Rep. **374**, 91 (2003).
[2] I. Bray *et al.*, Phys. Rep. **520**, 135 (2012).
[3] G. Gasaneo *et al.*, Adv. Quantum Chem. **67**, 153 (2013).
[4] M. J. Ambrosio *et al.*, J. Phys. B **48**, 055204 (2015).
[5] M. J. Ambrosio *et al.*, Phys. Rev. A **93**, 032705 (2016).
[6] M. J. Ambrosio *et al.*, Phys. Rev. A **92**, 042704 (2015).
[7] M. J. Ambrosio *et al.*, Eur. Phys. J. D **71**, 127 (2017).

SESSION RR1: PLASMAS AT SPECIAL CONDITIONS
Thursday Morning, 9 November 2017
Room: Salon D at 10:00
Mirko Vukovic, Tokyo Electron Ltd., presiding

Contributed Papers

10:00

RR1 1 Early Formation of Uranium Monoxide in Laser-Ablated Plasmas: Constraints on the Rate Coefficients from Ultrafast Spectrometry and Plasma-Chemistry Models* DAVIDE CURRELI, MIKHAIL FINKO, *University of Illinois at Urbana Champaign, Urbana, IL 61801* MAGDI AZER, *Illinois Applied Research Institute, Champaign, IL 61820* MIKE ARMSTRONG, JONATHAN CROWHURST, HARRY RADOUSKY, TIMOTHY ROSE, ELISSAIOS STAVROU, DAVID WEISZ, JOE ZAUG, *Lawrence Livermore National Laboratory, Livermore, CA 94550* The mechanisms regulating uranium chemical fractionation in post-detonation nuclear debris are not well understood. The fractionation process alters the chemistry of the nuclear debris so that it no longer reflects the chemistry of the source weapon. We have measured time-resolved vibronic emission spectra of uranium monoxide (UO) formed after laser ablation of the metal in gaseous oxygen. Tests with different oxygen isotopes of $^{238}U^{16}O$ and $^{238}U^{18}O$ have allowed to uniquely identify a convenient molecular emission line that can be tracked over time to characterize the kinetics of UO formation in the cooling plasma plume. Comparison with a Monte-Carlo Plasma Chemistry model including a detailed thermochemistry of uranium combustion has allowed for the first time to constrain the rate coefficients and highlight the dominant reaction pathways of UO formation in oxygen atmospheres.

*This project was sponsored by the DoD, Defense Threat Reduction Agency, Grant HDTRA1-16-1-0020. This work was performed in part under the auspices of the U.S. DoE by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

10:15

RR1 2 Sound generated by small perturbations of power in high-pressure arcs* FEDOR POPOV, MIKHAIL SHNEIDER, *Princeton University* We propose a simple analytical theory to describe the sound generated by small periodic perturbations of a cylindrical dc arc in a dense gas. Theoretical analysis was done within the framework of the conventional channel arc model with an effective channel radius and a given fluctuating Joule's heat. The arc channel model was supplemented with time-dependent gas dynamic equations. Estimation formulas for the generated sound intensity in the near field were obtained. In the peripheral region of an arc with graphite electrodes burning in a high pressure inert gas, a large number of microscopic soot particles are produced together with nanoparticles. Experimental studies have shown that exposure of the peripheral region of the arc to intense ultrasounds (~100–120 dB) lead to a noticeable increase in the efficiency of the synthesis of nanoparticles and to the reduction in the yield of soot [1]. It was shown in [2] that ultrasounds, acting on the suspension of soot microparticles and nanoparticles in gas result in the coagulation of soot particles, without noticeably affecting the small-scale nanoparticles. Our estimates show that relatively small perturbations of the power in a high-pressure arc (at the level of several percent) can be a source of high-intensity sound comparable to that used in experiments [1].

*This work was supported by the U.S. Department of Energy, Office of Science, Basic Energy Sciences, Materials Sciences and Engineering Division. FKP is grateful to the Grant of RFBR 16-32-00064-mol-a.

[1] G. N. Churilov, Nanotubes and Carbon Nanostructures **16**, 395 (2008).
[2] M. N. Shneider, AIAA 2016-1693, San Diego, CA (2016).

10:30

RR1 3 Hydrodynamic approach to modeling of plasma processes under the action of pulsed electron beam* NURKEN AKTAEV, GENNADY REMNEV, *Tomsk Polytechnic University* ALEXANDR YALOVETS, *South Ural State University* The investigation is devoted to the mathematical modeling of action of pulsed high intensity pulse electron beam (HIPEB) on one-component molecular gas. The characteristic parameters of HIPEB are: energy of electrons is 300–500 keV, current density is 500–1000 A/m^2, pulse duration is 100 nsec, and gas pressure is varied from 10 to 100 kPa. Under the action of PHPEB on gas the nonequlibrium plasma is formed. Because the beam energy is transferred to the gas through the electronic component the electron and ion temperatures vary significantly. The time for alignment of the temperatures is very large because of the relatively small pressures. The theoretical investigation of the plasma processes under the action of HIPEB has performed within the framework of one-liquid two-temperature hydrodynamic model. Because of the electron and ion temperatures vary significantly we use the separate equations for thermal balance. As a result of the numerical modeling the main channel of energy dissipation of electron beam is revealed. The energy pumping from electron to ion subsystem is also discussed.

*The research was supported by RFBR Project No. 16-32-00071 mol_a and by RSF Project No. 17-19-01442.

10:45

RR1 4 Analytical model of cold-cathode breakdown in helium at extremely high electric field and low pressure* LIANG XU, ALEXANDER KHRABROV, IGOR KAGANOVICH, *Princeton Plasma Physics Lab* TIMOTHY SOMMERER, *General Electric Global Research* PRINCETON PLASMA PHYSICS LAB COLLABORATION, GENERAL ELECTRIC GLOBAL RESEARCH COLLABORATION An analytical model is developed for gas ionization breakdown at extremely high values of reduced electric field (the ratio E/n of electric field to gas density) between parallel-plate electrodes in helium. The value of E/n under investigation varies in the range of 70–6600 kTd (1 kTd $= 10^{-18}$ Vm^{-2}) for $pd \sim 0.5$ Torr-cm, where p is the gas pressure and d is the electrode separation. The model includes anisotropic scattering for all species and fast neutral atom backscattering at electrodes, as well as fast-neutral impact ionization. The results are compared to those from a detailed Particle-In-Cell/Monte Carlo (PIC/MCC) simulation (Liang Xu *et al.*, "Investigation of the Paschen Curve for Helium in 100–1000 kV Range"), and to experimental measurements. Analytical model results are sufficiently accurate for $E/n \sim 1000$ kTd if the model treats the electrons as a single beam and assumes that charge exchange is the dominant collision process which determines the local distributions of ions and fast neutral atoms.

*This work was supported by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000298.

11:00

RR1 5 Overview of DOE/FES program activities for low temperature plasma science research NIRMOL PODDER, *U.S. Department of Energy* TBA

11:15

RR1 6 Overview of NSF plasma physics and low temperature plasma science and engineering programs VYACHESLAV (SLAVA) LUKIN, *National Science Foundation* TBA

11:30

RR1 7 NSF Low Temperature Plasma Workshop on Sustainability: Process, Findings, Path forward MARK KUSHNER, *University of Michigan* The workshop "Science Challenges in Low Temperature Plasma Science and Engineering: Enabling a Future Based on Electricity through Non-Equilibrium Plasma Chemistry", sponsored by the National Science Foundation and Army Research Office, was held August 2016 with the goal of defining the research challenges and the role of low temperature plasmas in sustainability. The workshop report, available at http://mipse.umich.edu/nsfworkshop/, broadly discusses challenges across the discipline, with emphasis on the focus areas of multiphase plasma systems, energy and the environment, biotechnology and food cycle, and synthesis and modification of materials. In this talk, the process and motivation for holding the workshop and the workshop findings will be discussed. The talk will encourage community wide strategic discussion, advocacy for a path forward, and engagement of Federal agencies in this initiative.

SESSION RR2: HIGH PRESSURE DISCHARGES

Thursday Morning, 9 November 2017
Room: Duquesne at 10:00
Svetlana Starikovskaya, Laboratoire de Physique des Plasmas (LPP) UMR CNRS, presiding

Contributed Papers

10:00

RR2 1 Development of ice dielectric barrier discharge for the development of novel reaction field in cryogenic environments NORITAKA SAKAKIBARA, TSUYOHITO ITO, KAZUO TERASHIMA, *University of Tokyo* Multi-phase plasmas, including plasma-liquid interactions, are now receiving increasing attention aiming for the wide range of applications. As a new type of multi-phase plasma, ice dielectric barrier discharge (DBD), whose dielectric barrier is made of ice, was generated at a wide range of cryogenic temperature from room temperature down to 6.5 K. We are expecting plasma-ice interaction system as a novel cryogenic reaction filed, taking advantage of selective chemical reactions on the ice surface. In this research, gas temperature was treated as a control parameter, and variations of optical emission spectra and discharge modes were observed. In particular, we revealed drastic change in power consumption of ice DBD in the vicinity of the melting point of water (273 K). This clearly indicates the importance of gas temperature as a control parameter in the research area of multi-phase plasmas. Moreover, in the presentation, we will present results of material synthesis with using the ice DBD, which is in progress.

10:15

RR2 2 Modeling of subnanosecond discharges in atmospheric-pressure air* GEORGE NAIDIS, NATALIA BABAEVA, *Joint Institute for High Temperatures, Russian Academy of Sciences* Development of pulsed discharges in high-pressure gases typically proceeds via the prebreakdown stage of formation and propagation of fast ionization waves – streamers. The use of voltage pulses with very steep, subnanosecond fronts supplies conditions when streamer formation occurs at strong overvoltages, resulting in generation of wide plasma channels, with radii of several millimeters [1,2]. Such plasma structures, similar to glow discharges, are of interest to various applications due to quasi-uniformity of plasma parameters in relatively large volumes. In this talk, results on computational study of subnanosecond discharge formation in atmospheric-pressure air are presented. The effects of rise time and polarity of applied voltage pulses are considered. A comparison of calculated discharge characteristics with experimental data is given. Possible role, in the discharge formation, of runaway electron beams and X-rays generated by the discharge is discussed.

*Work is supported by the Russian Science Foundation (Project Number 14-50-00124).

[1]D. V. Beloplotov, V. F. Tarasenko, M. I. Lomaev, and D. A. Sorokin, IEEE Trans. Plasma Sci. **43**, 3808 (2015).
[2]P. Tardiveau, L. Magne, E. Marode, K. Ouaras, P. Jeanney, and B. Bournonville, Plasma Sources Sci. Technol. **25**, 054005 (2016).

10:30

RR2 3 Spectroscopic measurement of the electric field in a helium plasma jet MARLOUS HOFMANS, ANA SOBOTA, *Eindhoven University of Technology* The electric field in a plasma jet is measured spectroscopically utilizing the Stark-effect. A cold atmospheric pressure helium plasma jet is used, which operates at a μs-pulsed applied voltage of 6 kV, a frequency of 5 kHz and with a helium flow of 1.5 slm. Due to the electric field in the jet, the forbidden and allowed bands of the emission spectrum shift. This is called the Stark-effect. The spectrum of both the He I 492.2 nm line and the He I 447.1 nm line are obtained with an iCCD-camera coupled to a monochromator. From the peak-to-peak wavelength difference between the allowed and forbidden band, the electric field in the jet is calculated. The electric field is determined both inside and outside the capillary of the jet, up to 2 cm in the effluent of the jet. Furthermore, the electric field in the jet is determined, while a target is placed close to the end of the capillary. Grounded and non-grounded, conducting and insulating targets are used and placed at different distances.

10:45

RR2 4 Student Excellence Award Finalist: Atmospheric Pressure Plasma Multi-jets: Fundamental Properties* AMANDA M. LIETZ, *University of Michigan* XAVIER DAMANY, JEAN-MICHEL POUVESLE, ERIC ROBERT, *GREMI Universite d'Orleans* MARK J. KUSHNER, *University of Michigan* A multi-jet plasma source is being developed for large area treatment of surfaces with atmospheric pressure plasma. The multi-jet source is a dielectric tube, capped at the end, with a row of holes aligned on one side. Helium flows through the tube and out the holes, where plumes of the He mix with ambient humid air. An ionization wave (IW) begins at a powered electrode upstream of the holes, propagates along the tube and, passing each hole, launches a separate, secondary ionization wave (SIW) through the hole which extends toward a grounded pump below. The parameters which effect this system have been investigated using *nonPDPSIM*, a 2-D plasma hydrodynamics model. The hole diameter determines the velocity of the SIW as it passes through the holes by controlling the angle of the electric field within the holes. A higher helium flow rate results in a larger region of purer helium outside of the tube, extending the distance the SIW can propagate outside of the hole before encountering air. Positive voltage polarity produces a plasma within the tube which does not hug the wall as tightly, and increases the intensity of the SIW outside of the tube. Comparisons will be made to experimental ICCD imaging of the primary IW and SIW, for which there is good agreement.

*Supported by the NSF and DOE Fusion Energy Sciences.

11:00

RR2 5 Experimental and modeling results on the axial and radial breakdown dynamics in dielectric barrier discharges HANS HÖFT, MARKUS M. BECKER, DETLEF LOFFHAGEN, MANFRED KETTLITZ, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* The breakdown of dielectric barrier discharges (DBDs) was investigated with respect to its axial and radial development. For this purpose, a pulsed-driven, single-filament DBD at atmospheric pressure (0.1 vol% O_2 in N_2) with 1 mm gap was used. The experimental diagnostics consisted of an iCCD and a streak camera system (50 ps temporal and 10 μs spatial resolution) combined with fast electrical probes. Additionally, time-dependent, spatially 2D fluid model calculations were performed. A correlation of the axial (cathode-directed) streamer propagation and the streamer diameter was found, i.e. this diameter increases with the axial propagation velocities. Furthermore, the radial expansion velocities ($\sim 10^5$ m/s) during the streamer breakdown phase also increase with the axial propagation velocities ($\sim 10^6$ m/s). The analysis of the radial dynamics allows the separation of the streamer propagation and the transient glow phase during the channel formation, i.e. the discharge channel widens, when the cathode-directed streamer hits the cathode surface. By means of synchronized measurements of the electrical current and the emission intensity, the temporally resolved current density could be determined in reasonable agreement with the modelling results.

11:15

RR2 6 Spatially-resolved electron temperature in a helium cold RF discharge up to atmospheric pressure JEAN-SEBASTIEN BOISVERT, *Institut national de la recherche scientifique, Varenne, Canada* NATHAN MAUGER, LUC STAFFORD, *Departement de physique, Universite de Montreal, Montreal, Canada* FRANCOIS VIDAL, *Institut national de la recherche scientifique, Varenne, Canada* JOELLE MARGOT, *Departement de physique, Universite de Montreal, Montreal, Canada* A cold plasma is generated inside a dielectric tube (inner diameter of 2 mm) using two long linear electrodes painted on diametrically opposed sides of the tube. The plasma can be sustained in helium from 10 to 760 Torr without any gas flow. In order to evaluate the electron temperature, a collisional-radiative model is coupled with optical emission spectroscopy of He ($n = 3$) lines. At atmospheric pressure, the spatially averaged T_e increases from 0.2 to 2 eV when the power density is increased from 2 to 12 W cm^{-3} (associated to the transition from the Ω to γ mode). With the help of a camera equipped with different band-pass filters (around 667 and 728 nm), the same collisional-radiative model is used to obtain the spatially-resolved electron temperature in the γ mode. It is about 0.5 eV in the bulk but 4 eV in the sheath region, this is in agreement with modelling of plane-parallel CCRF discharges in the literature. When the pressure is decreased below atmospheric pressure, the sheaths broaden and the region of high electron temperature (>2 eV) fills the whole tube diameter. In addition, below 100 Torr, a plasma column is generated outside the electrode area, T_e in this region being much lower than between the electrodes.

11:30

RR2 7 An Investigation of the Effect of Pressure Variations on Micro-Discharge Formation and Propagation in a 2-D Packed Bed Reactor* KENNETH ENGELING, JULIUSZ KRUSZELNICKI, JOHN FOSTER, MARK KUSHNER, *Univ of Michigan - Ann Arbor* Packed bed dielectric barrier discharge reactors (PBRs) are one of the technologies at the forefront of advanced plasma applications such as plasma-aided combustion, dry reforming of methane, and plasma catalysis. Plasma formation and propagation occurs through the porous media of the PBR in the form of microdischarges and are a function of several parameters. To investigate the kinetic mechanisms of the micro-plasma formation, a 2-dimensional packed bed reactor was designed for optical analysis. The 2-d array of dielectric aggregate with varying dielectric constants is used to simulate and visualize plasma formation as a function of voltage, pressure, gas type, and spacing to gain insight into actual packed bed discharge operation. In this work, we focus particularly on discharge evolution as a function of pressure from sub-atmospheric pressure to 1 Atm. The 2-d geometry is directly observed using fast camera imaging and emission spectroscopy. Microdischarges in the 2-D array are studied with both ns-pulsed discharge excitation as well as low frequency AC excitation.

*Work supported by US DOE Office of Fusion Energy Science and the National Science Foundation.

11:45

RR2 8 Hydrodynamic effects induced by nanosecond sparks in ambient air* SERGEY STEPANYAN, NICOLAS MINESI, GABI-DANIEL STANCU, CHRISTOPHE LAUX, *EM2C Laboratory, CNRS UPR288, CentraleSuplec* This work presents the results on hydrodynamic effects induced by nanosecond repetitive sparks in ambient air. In order to monitor the hydrodynamic effects, four optical diagnostics were combined: emission spectroscopy, Planar Laser Induced Fluorescence, Schlieren and fast imaging. The mentioned diagnostics were synchronized with electrical energy measurements to (i) observe the spatial distribution of gas temperature and active species produced in the discharge afterglow, (ii) investigate hydrodynamic coupling between the discharges at high frequencies of applied pulses. One of the major experimental findings was the synergy between the discharges at higher frequencies (>1 kHz). The volume occupied by hot gas and active species after a burst of N sparks is larger than N times the volume occupied after a single discharge. It has been demonstrated that the energy density in the case of high-frequency discharge redistributes spatially during a period shorter than the typical ignition delay time. It has also been shown that the value of the energy density is sufficient for ignition of lean mixtures. Therefore we believe that this effect can be used as an efficient tool for volumetric ignition that can improve the combustion of lean mixtures. .

*FAMAC project (Grant No. ANR-12-VPTT-0002), PLASMAFLAME project (Grant No. ANR-11-BS09-0025).

SESSION RR3: ELECTRON-MOLECULE COLLISIONS

Thursday Morning, 9 November 2017; Room: Oakmont Junior Ballroom at 10:00; Murtakha Khakoo, California State University Fullerton, presiding

Invited Papers

10:00

RR3 1 Adiabatic-nuclei calculations of electron and positron scattering from molecular hydrogen and its ion*

DMITRY FURSA, *Curtin Univ of Technology*

We report the extension of the convergent close-coupling (CCC) method for electron-molecule scattering [1] to the adiabatic-nuclei (AN) formulation which allows us to study the effects of nuclei motion and electron-impact dissociation processes. For H_2^+ and its isotopologues [2] we have modeled collisions with hot (vibrationally excited) molecules and compared with available experimental data for dissociative ionization, proton production, and the dissociative products kinetic energy release distributions. For H_2 we have performed AN calculations of positron scattering with emphasis on establishing convergent low-energy total and vibrational $0 \rightarrow 1$ excitation cross sections. To study electron collisions with H_2 we have developed a spheroidal coordinate formulation of the CCC method that allows for an accurate description of the target wave functions to large inter-nuclei distances. Excitation cross sections for vibrationally resolved transitions between low-lying H_2 states have been calculated and used to determine vibrational excitation of the H_2 ground state via excitation of electronically excited singlet states and radiative cascade.

*Work supported by Curtin University, Pawsey Supercomputing Centre, LANL, and the US Air Force Office of Scientific Research. In collaboration with: M. C. Zammit, J. S. Savage, L. H. Scarlett, J. Tapley, and I. Bray.

[1]Zammit *et al.*, J. Phys. B **50**, 123001 (2017).
[2]Zammit *et al.*, Phys. Rev. A **90**, 022711 (2014).

10:30

RR3 2 Fragmentation dynamics of simple molecules by electron collision

XIANGJUN CHEN, *University of Science and Technology of China*

The dissociation of multi-charged molecule is of great importance in various fields, such as plasma physics and planetary atmospheric chemistry. Most of the multi-charged molecules are in transient states that always dissociate through various pathways, which contain valuable information of the potential energy surfaces of the molecular ions. Recently, the three-body fragmentation dynamics of multi-charged CO_2, OCS, CS_2 molecules have been studied by electron collision using momentum imaging technique in my group. Nonsequential and sequential fragmentation dynamics of CO_2^{3+} has been investigated by electron collision at an impact energy of 500 eV. The dissociation mechanisms are clearly distinguished by combined use of the Dalitz plot together with momentum correlation spectra. The angular distributions and kinetic-energy releases (KERs) of different fragmentation processes are obtained. By analyzing KERs together with the help of potential-energy curves exploration at the multi-reference configuration interaction level, we conclude that the sequential fragmentation occurs in the ground state and the first two low-lying electronic excited states of the CO_2^{3+} ion. Fragmentation dynamics of CO_2^{4+} are also analyzed and the distributions of momentum correlation angles between ionic fragments and the KERs are obtained. Based on the Coulomb explosion model, the bond angle and the bond length of CO_2^{4+} before fragmentation are reconstructed. The results agree quite well with the geometry parameters of neutral CO_2 molecule. We also investigated the fragmentation dynamics of OCS^{q+} and CS_2^{q+} (q = 2, 3, 4) induced by electron collision at an impact energy of 500 eV using the momentum imaging technique. Various dissociation channels are analyzed in details. Recently, we have performed molecular dynamics simulation of the ground state of CO_2^{3+}. The evolution of the molecular bond breakage in time range of 0–200 fs is investigated. The results will be presented in the talk.

Contributed Papers

11:00

RR3 3 Low energy (e, 2e) study for N_2 in coplanar and non-coplanar geometries for symmetric and asymmetric angles and final state electron energies* SADEK AMAMI, *Missouri University of S&T, Rolla, Mo 65409* AHMAD SAKAAMINI, MATTHEW HARVEY, ANDREW MURRAY, *Photon Science Institute, School of Physics & Astronomy, University of Manchester, Manchester M13 9PL, UK* DON MADISON, *Missouri University of S&T, Rolla, Mo 65409* Triple differential cross sections (TDCS) have been calculated and compared with experimental data for electron impact ionization of the neutral molecule N_2 over a range of geometries from coplanar to the perpendicular plane. Experiment and theory will be compared for incident electron energies of 10 eV and 20 eV above the ionization potential of the $3\sigma_g$, $1\pi_u$ and $2\sigma_g$ states, using both equal and non-equal outgoing electron energies. Also, we have measured and calculated TDCS for equal outgoing electron energies of 10 eV and 20 eV for ionization of the N_2 $3\sigma_g$, and $1\pi_u$ states for one of the electrons having a fixed scattering angle of 45°, 90°, and 125°. Calculations have been done for experimental data taken with the incident electron beam in the scattering plane, at 45° to this plane and orthogonal to the scattering plane. Experimental data will be compared to three different theoretical approximations - the three body distorted wave (3DW) approximation, the Distorted wave Born approximation (DWBA), and the Ward-Macek approximation.

*This work supported by NSF.

11:15

RR3 4 Electron impact single ionization of methane LORENZO UGO ANCARANI, *Universite de Lorraine, Metz, France* CARLOS MARIO GRANADOS-CASTRO, *Martin-Luther-Universitat Halle-Wittenberg, Germany* The electron impact single ionization of the outer valence $1t_2$ and the inner valence $2a_1$ orbitals of methane is investigated theoretically. In a first Born approximation, the scattering wave function describing the ejected electron is expanded in a set of Generalized Sturmian Functions [1] with appropriate Coulomb asymptotic conditions; this allows us to extract the scattering amplitude directly from the expansion coefficients, without the need of calculating a transition matrix element. Triple differential cross sections, calculated for several coplanar asymmetric geometries, are compared with other theoretical models (in an absolute scale), and with two sets of relative scale measurements with incident energies of 500 eV or 250 eV [2,3]. The binary to recoil ratio is analyzed as a function of the momentum transfer. For the outer valence $1t_2$ and for given kinematical conditions, we predict a double peak structure in the cross section binary region, a clear signature of the p-nature of the molecular orbital.

[1]C. M. Granados-Castro and L. U. Ancarani, Eur. J. Phys. D **71**, 65 (2017).
[2]A. Lahmam–Bennani *et al.*, J. Phys. B **42**, 165201 (2009).
[3]N. Isik *et al.*, J. Phys. B **49**, 065203 (2016).

11:30

RR3 5 Self-consistent electron impact cross-sections for THF: A swarm investigation* MADALYN CASEY, DANIEL COCKS, GREGORY BOYLE, *James Cook University* JAIME DE URQUIJO, *Universidad Nacional Autonoma de Mexico* DARRYL JONES, MICHAEL BRUNGER, *Flinders University* RONALD WHITE, *James Cook University* An accurate quantitative description of electron transport in biological systems is necessary for applications in medical imaging and dosimetric treatments. Modelling charged particle transport in the human body on a molecular level involves interactions with many complex molecules but is often reduced to the comprehensively studied surrogate of water. Simple analogues for the sugars and DNA bases, such as tetrahydrofuran (THF), a sugar linking the phosphate groups in the DNA backbone, represents a first step to include the structure of DNA. The first experiments of macroscopic transport of electrons in pure THF and mixtures with N_2 and Argon have become available, and we use these measurements to perform rigorous testing of existing THF cross-sections. To model transport through THF we solve Boltzmann's equation to iteratively modify cross-sections and obtain a set that best reproduces the experimental transport coefficients. Negative differential conductivity is present in mixtures with THF, but is absent in the pure gas, and we observe the thermal activation of this phenomenon.

*Work partially supported by Conacyt (240073) and PAPIIT (IN108417), and the Australian Research Council.

11:45

RR3 6 Theoretical and experimental study of electron impact ionization (e,2e) of para-benzoquinone for an intermediate incident electron energy ESAM ALI, *Missouri Univ of Sci & Tech* DARRYL JONES, *School of Chemical and Physical Sciences, Flinders University, GPO Box 2100, Adelaide SA 5001, Australia* ODDUR INGLFSSON, *Science Institute and Department of Chemistry, University of Iceland, Dunhagi 3, 107 Reykjavik, Iceland* CHUANGANG NING, *Department of Physics and State Key Laboratory of Low-Dimensional Quantum Physics, Tsinghua University, Beijing 100084, China* JAMES COLGAN, *Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA* MICHAEL BRUNGER, *School of Chemical and Physical Sciences, Flinders University, GPO Box 2100, Adelaide SA 5001, Australia* DON MADISON, *Missouri Univ of Sci & Tech* We will present a theoretical and experimental study of electron impact single ionization of para-benzoquinone [1]. Experimental data were taken for the unresolved combination of the 4 highest occupied molecular orbitals (4b3g, 5b2u, 1b1g, and 2b3u) of para-benzoquinone. The theoretical results are compared with experimental data measured in an asymmetric coplanar geometry for a 250 eV incident electron energy, an ejected electron energy of 20 eV, and for four fixed scattered electron angles of 7.5°, 10°, 12.5°, and 15°. Theoretical M3DW (molecular 3-body distorted wave) results summed over the four unresolved states will be compared to the experimental data. As the experimental TDCS measurements for each scattering angle are cross normalized, we fully assess the ability of the theoretical model to reproduce the experimental data in terms of angular distribution and intensity.

[1]Jones *et al.*, J. Chem. Phys. **145**, 164306 (2016).

SESSION SR1: MODELING AND SIMULATION II

Thursday Afternoon, 9 November 2017; Room: Salon D at 13:30; Francesco Taccogna, CNR Nanotec, presiding

Invited Papers

13:30

SR1 1 An advanced particle-in-cell simulation parallelized with GPUs for a capacitively coupled plasma reactor
HAE JUNE LEE, *Pusan National University*

Many key aspects of low-temperature plasmas include nonlinear transient and kinetic effects related to the spatiotemporal variation of electron energy distribution function (EEDF) which cannot be treated in a fluid simulation model. The particle-in-cell (PIC) simulation calculates kinetic effects through the statistical representation of the EEDF using many particles and thus gives accurate results. However, the computational cost is very expensive to resolve all aspects in a plasma discharge with millions of particles as well as hundreds of thousand of grids during millions of time steps. Additionally, the simulation of discharge plasmas should handle the collision processes and the rapid increase of the total number of simulation particles. In this presentation, details of a two-dimensional PIC simulation parallelized with graphics processing units (GPUs) are explained for the improvement of computation speed. For the simulation of a capacitively coupled plasma reactor with a gas pressure from 10 mTorr to 3 Torr, various kinetic effects are analyzed with the GPU-PIC code by investigating the spatiotemporal variation of EEDFs and electron heating. Finally, the changes of ion energy and angle distribution functions on the substrate are presented with the increase in gas pressure.

Contributed Papers

14:00

SR1 2 Particle in Cell Algorithms and Codes Toward the Next Generation Architectures ARAM MARKOSYAN, CHRISTOPHER MOORE, MATTHEW BETTENCOURT, JANINE BENNETT, JONATHAN LIFFLANDER, DAVID HOLLMAN, JEREMIAH WILKE, HEMANTH KOLLA, *Sandia National Laboratories* Massively parallel and heterogeneous next-generation platforms present unprecedented challenges for maximizing efficiency of plasma simulation kernels. Asynchronous many-task (AMT) frameworks use deferred execution and asynchronous tasking to enable runtime capabilities ranging from load balance to data reuse to communication overlap. Many AMT systems are large full stack frameworks with certain programmability or stability concerns, limiting their use in Sandia production codes. We have developed DARMA (Distributed Asynchronous Resilient Models for Application), which instead provides a light-weight translation layer for embedding tasking and deferred execution in C++ codes that encourages, rather than restricts, flexible and diverse AMT software stacks. In this work, we focus on leveraging DARMA to better express asynchrony and load imbalance present in particle in cell kernels. In particular, we present empirical performance and productivity results, where DARMA implementation of these kernels is compared to more traditional implementations.

14:15

SR1 3 Particle-in-Cell modeling of the magnetized direct current microdischarge* DMITRY LEVKO, LAXMINARAYAN RAJA, *The University of Texas at Austin* Following the Paschen's law, electrical breakdown of gaps with small *pd*, where *p* is the gas pressure and *d* is the interelectrode gap, requires extremely high voltages. This means that the breakdown voltage for low-pressure microdischarges is of the order of a few kilovolts. This makes impractical the generation of low-pressure dc microdischarges. The application of dc magnetic field confines electrons in the cathode-anode gap. This leads to the significant decrease of the breakdown voltage because each electron experiences many collisions during its diffusion toward the anode. However, as was obtained experimentally, magnetized low-pressure microdischarges experience numerous instabilities whose nature is still not completely understood. In the present paper, we study the influence of magnetic field on the low-pressure microdischarges. We use self-consistent one-dimensional Particle-in-Cell Monte Carlo collisions model which takes into account the electron magnetization while ions remain unmagnetized. We obtain striations in the discharge. We show that these striations appear in both homogeneous and non-homogeneous magnetic field. We find simple expression for the instability growth rate which shows that the instability results from ionization processes.

*Air Force Office of Scientific Research (AFOSR) through a Multi-University Research Initiative (MURI) Grant titled "Plasma-Based Reconfigurable Photonic Crystals and Metamaterials" with Dr. Mitat Birkan as the program manager.

14:30

SR1 4 PIC/MCC simulation of magnetized capacitively coupled plasmas SHALI YANG, *Huazhong University of Science and Technology* YA ZHANG, *Wuhan University of Technology* HONGYU WANG, *Anshan Normal University* WEI JIANG, *Huazhong University of Science and Technology* Magnetized capacitively coupled plasma (MCCP) has been widely used in microelectronic industry. External magnetic field is applied to increase the efficiency of power transfer to the plasma and enhance plasma confinement. We used our one-dimensional implicit Particle-in-cell/Monte Carlo collision (PIC/MCC) model to study the symmetric and asymmetric magnetic field on CCP. The PIC/MCC model is one-dimensional in space and three-dimensional in velocity, thus the E×B drift is correctly simulated. For the symmetric magnetic field, we studied the electrical asymmetry effects in MCCP. It is found that, with a weaker magnetic field at 10 G, the plasma density is nearly doubled and the self-bias is almost unaffected. And with a stronger magnetic field at 100 G, the plasma density is significantly increased and nearly independent of the phase angle, but at the cost of decreasing the self-bias, which results in a smaller adjustable range of ion bombardment energy. For the asymmetric magnetic field, we studied magnetical asymmetric effect (MAE) in a geometrically and electrically symmetric CCP. It has demonstrated that MAE will generate a DC self-bias and asymmetric plasma response. It can be an effective means to control the plasma properties as an augmentation to conventional measures.

14:45

SR1 5 Large Scale Simulations of the Plasma-Material Interaction using Electrostatic Particle-in-Cell Code hPIC* RINAT KHAZIEV, STEVEN MARCINKO, CAMERON DART, ALYSSA HAYES, DAVIDE CURRELI, *Univ of Illinois - Urbana* Advancements have been made in the development of the kinetic-kinetic electrostatic Particle-in-Cell code hPIC, designed for large-scale simulations of the Plasma-Material Interface. The Algebraic Multigrid Solver BoomerAMG from the PETSc library was utilized to achieve a weak scaling efficiency of 87% on more than 64,000 cores of the BlueWaters supercomputer at the University of Illinois at Urbana-Champaign. The code has been validated in two-stream instability simulations and can simulate a volume of plasma over several square centimeters of surface extending out to the pre-sheath of plasma in kinetic-kinetic mode. Results from a parametric study of the plasma sheath in fusion relevant conditions will be presented, as well as a detailed analysis of the plasma sheath structure at grazing magnetic angles. The distribution function and its moments will be reported for plasma species in the simulation domain and at the material surface for plasma sheath simulations.

*Work supported by the NCSA Faculty Fellowship Program at the National Center for Supercomputing Applications; supercomputing resources provided by Exploratory Blue Waters Allocation.

Invited Papers

15:00

SR1 6 Modeling streamer discharges in strong magnetic fields: from particle to fluid*
JANNIS TEUNISSEN, *Centre for Mathematical Plasma Astrophysics, KU Leuven, Belgium*

In atmospheric air, streamer discharges become magnetized in a magnetic field of a few tens of Tesla. Such strong magnetic fields are experimentally hard to realize, but they can easily be incorporated in a particle model. However, particle-in-cell simulations are computationally expensive, in particular when they need to be performed in 3D. Therefore, I have developed a plasma fluid model for discharges in external magnetic fields. This open-source model uses multi-dimensional electron transport data tables, generated by a Monte Carlo Boltzmann solver. It furthermore includes adaptive mesh refinement and a parallel Poisson solver, making use of the Afivo framework. Two- and three-dimensional numerical simulations show that positive streamers preferably grow parallel to the magnetic field. If the background electric and magnetic field are parallel, the magnetic field accelerates streamers while reducing their radius. For a perpendicular field configuration, deterministic streamer branching parallel to the magnetic field is observed. Surprisingly, the $\vec{E} \times \vec{B}$ drift plays no major role for positive streamers, whereas it does affect negative streamers. One application of the results is the understanding of sprite discharges on Jupiter, which could well be magnetized due to the stronger planetary magnetic field.

*Research performed in collaboration with A. Sun and U. Ebert. JT is supported by FWO postdoctoral fellowship 12Q6117N.

SESSION SR2: PLASMAS IN LIQUIDS II
Thursday Afternoon, 9 November 2017
Room: Duquesne at 13:30
Tanvir Farouk, University of South Carolina, presiding

Contributed Papers

13:30

SR2 1 Electrical Breakdown of Weakly-Conductive Liquids and Transition to a Supercritical Fluid* SKYE ELLIOTT, SERGEY LEONOV, *Univ of Notre Dame* ND TEAM This experimental study reveals the high-voltage pulsed electrical breakdown of weakly-conductive liquid (MeOH) trapped in a dielectric test cell. It is considered a three-phase process with (1) mm-scale streamers propagation, (2) formation of a highly-conductive channel, and (3) transition of the discharge in liquid to in a supercritical fluid. Typical test conditions are: voltage applied U>10 kV; electrical current I>100 A; initial pressure P=1 bar; maximal pressure within supercritical fluid P>100 bar. The diagnostics include: electrical probes, fast camera imaging, schlieren visualization of hydrodynamic processes, laser tracking of interfaces, optical emission spectroscopy. The sequence of plasma formation and supercritical fluid generation were shown to be highly sensitive to electrode configuration and applied voltage, with lower voltages yielding a two-step delayed breakdown. A non-ideal plasma state is considered with electron density $Ne > 3\times19\ cm^{-3}$ measured by Stark broadening of Hα line. Study of mechanisms of electric breakdown and discharge dynamics in supercritical fluids is a fundamental challenge and promises well-recognized practical benefits, such as a fuel injection technique, protection against deadly breakdowns in electrically-insulating liquids, etc.

*FlowPAC Institute.

13:45

SR2 2 Self-organization and Electrolyte Ion Mass Transport Processes with Chemistry in 1 ATM DC Glows YAO KOVACH, *University of Michigan Ann Arbor* MARIA GARCIA, *University of Cordoba* JOHN FOSTER, *University of Michigan Ann Arbor* In plasma physics, self-organization is observed in phenomena ranging from plasmoid formation in low pressure, RF plasmas to large-scale, and magnetized structures observed on the surface of the sun. Of recent interest is the puzzling information of self-organization patterns on the surface of liquid anodes in 1 ATM DC glows. While these patterns are of academic interest in regards to understanding collective phenomena, the appearance of the patterns may play an important role in the sub-surface liquid phase chemistry, driving convection and inducing thermal gradients. In this current work, a new, complex, star-shaped structure with round edges was observed with a copper sulfate electrolyte. The pattern was not observed with sodium chloride solutions. This observation suggests that electrolyte ion mass or perhaps ionization state may play a key role in deterring overall pattern shape. In order to understand the role of the transport of electrolyte ions from liquid to the gas phase on discharge maintenance, and pattern formation, spectroscopic analysis of the halo surrounds the main plasma column for multiple electrolytes are studied as a function of discharge conditions.

Invited Papers

14:00

SR2 3 Understanding the Plasma-Liquid Interface: Progress and Challenges*
JOHN FOSTER, *The University of Michigan-Ann Arbor*

The interaction of plasma with liquid water occurs at a phase boundary layer, which includes gas, a water vapor layer, and the liquid itself. A host of physical and chemical processes are active at this interface making it a rich multiphase physics problem. These processes ultimately give rise to changes in the bulk liquid. Such induced changes are the basis for a number of emerging technologies and applications such as plasma-based water treatment and plasma medicine. The nature of the physical processes and ensuing chemistry that "activates" the liquid water, which is believed to originate at the interface, is not well understood. Ongoing experimental and computational efforts however are making progress towards the formulation of a consistent picture of the role of the plasma liquid interface in driving chemistry in solution. Here we survey the current state of understanding regarding the interfacial region including electrohydraulic forces that can lead to fluid dynamical effects resulting in enhanced radical distribution as well as chemistry driven by direct plasma interaction with liquid water. In particular, we review recent results from single and 2-D bubble studies that have yielded insight into mechanisms of radical transport into solution as a function of discharge type present in the bubble. Complex mass transport and induced chemistry generated in DC atmospheric pressure glows with liquid electrode resulting from plasma self-organization is also not well understood. Insight into the physical mechanism underlying both self-organization and its role in radical transport in these systems as inferred from recent experiments is also discussed. The implications of these findings, the understanding gaps along with measurement and modeling needs for continued progress, and the connection of this understanding with technologies with a plasma liquid underpinning are also commented upon.

*DOE DE-SC 0002588, NSF CBET 1336375, and NASA Glenn.

Contributed Papers

14:30

SR2 4 Simultaneous particle image velocimetry (PIV)-Schlieren photography of fluid flow in liquid induced by plasma-driven interfacial forces JANIS LAI, JOHN FOSTER, *University of Michigan* UNIVERSITY OF MICHIGAN TEAM Understanding the transport of plasma-derived reactive species into bulk liquid is crucial for effective plasma-based water purification and other environmental applications. Physical and chemical interactions at the plasma-liquid interface region drive flow in the bulk liquid. The mechanisms of such flow are not well-understood. A 2-D plasma-in-liquid apparatus is used to study this interface region to understand the plasma-driven fluid dynamics. Previous shadowgraphs showed density gradients in the bulk liquid, while particle image velocimetry (PIV) measurements showed the velocity shear at the interface region. These measurements indicate the presence of fluid instabilities. Using simultaneous PIV-Schlieren photography, the interplay effect of such instabilities observed in the bulk liquid is investigated to better understand the plasma-driven forces at the interface, such as possible contribution of Marangoni flow.

14:45

SR2 5 Chemical reactions induced by plasma in contact with the solution containing halide ions: importance of ion distribution at gas-liquid interface for plasma-liquid interaction* KOSUKE TACHIBANA, KOICHI YASUOKA, *Department of Electrical and Electronic Engineering, Tokyo Institute of Technology* Plasma in contact with liquid is widely studied for the research of water purification, nanoparticle synthesis, and so on. However, plasma-liquid interaction has not been fully understood. In order to deepen the understanding of the plasma-liquid interaction, we are focusing on ion distribution at gas-liquid interface and using halide ions of chloride and iodide ions. That is because these ions have similar chemical properties but different distributions at the gas-liquid interface. There is a paper reporting that chloride ions exist in a region a little away from the gas-liquid interface while iodide ions gather at the gas-liquid interface. In order to investigate the importance of the ion distribution at the gas-liquid interface, we irradiated a DC plasma to 2.1 mol/L NaCl and NaI solution. The DC plasma was generated between a metal pin electrode and water surface in argon atmosphere, and the current was regulated at 2 mA. Though the DC plasma could not oxidize chloride ions into chlorine in the 2.1 M NaCl solution within 600 s, the plasma was able to oxidize iodide ions into iodine in the 2.1 M NaI solution within 20 s. The experimental results have shown that the ion distribution at gas-liquid interface can play an important role in the plasma-liquid interaction.

*This work was supported by JSPS KAKENHI, Grant-in-Aid for JSPS Fellows, Grant Number JP15J11924.

15:00

SR2 6 Electrostatic Debye layer formed at a plasma-liquid interface DAVID GO, PAUL RUMBACH, JEAN PIERRE CLARKE, *University of Notre Dame* Many of the new applications of low-temperature plasma in medicine and material synthesis rely on the direct interaction of plasma with an aqueous media. In this work, we derive and experimentally test an analytic model for the electrostatic Debye layer formed at a plasma-liquid interface [1]. Our theoretical model combines the Gouy-Chapman theory of aqueous electrolytes with a simple parabolic band model for the plasma sheath, and it gives closed form expressions for the electric field and charge distribution at the interface. It also predicts the plasma current density as a function of the solution ionic strength, which we experimentally confirmed using a liquid anode plasma. Fitting the model to the experimental data yields a plasma electron density on the order of 10^{19} m^{-3} and an electric field on the order of 10^4 V/m on the liquid side of the interface. Importantly, this work clearly shows that the plasma behavior and the electrostatics of the plasma-liquid interface are highly dependent on the ionic strength of the aqueous solution.

[1]P. Rumbach, J. P. Clarke, and D. B. Go, Phys. Rev. E **95**, 053203 (2017).

15:15

SR2 7 Interactions between water droplets and atmospheric pressure plasmas* JULIUSZ KRUSZELNICKI, AMANDA M. LIETZ, MARK J. KUSHNER, *University of Michigan* Atmospheric pressure plasmas are being studied for their potential application in water purification and agriculture. Transfer of plasma produced reactivity to the micro-droplets is potentially efficient due to the high surface area to volume ratio. We present results from a modeling study of the interactions between water micro-droplets and dielectric barrier discharges. The modeling is the plasma hydrodynamics simulator, *nonPDPSIM*. Spherical water droplets (5–20 μm) were placed into a 2 mm gap between dielectric-covered electrodes. For spherical water droplets ($\varepsilon_r \approx 80$), dielectric polarization results in local electric field enhancement at the poles of the droplet. During the discharge, this enhancement increases the electron temperature near the poles, which can launch ionization waves (IW) from the droplet. Since the IW interaction time is short compared to the dielectric relaxation time of the droplet, charge deposition occurs at the boundary, leading to an initial anisotropy in the species produced in the droplet. Large droplets depleted the local gas-phase densities of reactive species, which leads to a radius-dependent saturation of densities and pH. Liquid-phase saturation densities of reactive species strongly depends on their Henry's Law constants, *h*. Low-*h* species, such as O_3, saturate rapidly invariant of the droplet size, whereas high-*h* species (e.g., H_2O_2, NO_2, N_2O_5) do not saturate and become transport limited in getting reactants to the droplet.

*Supported by the NSF and DOE Fusion Energy Sciences.

SESSION SR3: CAPACITIVELY COUPLED PLASMAS
Thursday Afternoon, 9 November 2017
Room: Oakmont Junior Ballroom at 13:30
Rochan Upadhyay, Esgee Technologies Inc., presiding

Contributed Papers

13:30

SR3 1 The effects of realistic heavy particle induced secondary electron emission coefficients on the electron power absorption dynamics in capacitively coupled plasmas* JULIAN SCHULZE, MANASWI DAKSHA, *Ruhr-University Bochum, Germany* ARANKA DERZSI, *Wigner Research Centre for Physics, Hungary* SEBASTIAN WILCZEK, JAN TRIESCHMANN, *Ruhr-University Bochum, Germany* THOMAS MUSSENBROCK, *Brandenburg University of Technology, Germany* PETER AWAKOWICZ, *Ruhr-University Bochum, Germany* ZOLTAN DONKO, *Wigner Research Centre for Physics, Hungary* The effects of implementing energy-dependent secondary electron emission coefficients (SEEC) for ions and fast neutrals in PIC/MCC simulations of single and dual frequency capacitive discharges operated in argon are investigated. The surface conditions are taken into account, i.e. clean (heavily sputtered) and dirty (e.g. oxidized) metal surfaces are used. In single-frequency discharges the pressure and voltage at which the transition between the α- and γ-mode occurs are found to be significantly different compared to simulations based on constant SEECs and to strongly depend on the surface conditions. In classical dual-frequency discharges the effective SEEC significantly increases as a function of the low-frequency voltage amplitude for dirty surfaces due to its effect on the heavy particle energies at the electrodes. This is found to negatively influence the quality of the separate control of ion properties at the electrodes. These new results on the separate control of ion properties indicate significant differences compared to previous results obtained with constant SEECs.

*Funding: US NSF Grant No: 1601080, DFG SFB TR 87.

13:45

SR3 2 Nonlinear electromagnetics model of an asymmetrically driven capacitive discharge* M.A. LIEBERMAN, EMI KAWAMURA, A.J. LICHTENBERG, *University of California, Berkeley* DE-QI WEN, *Dalian University of Technology, Dalian, China* It is well-known that standing waves exist in high frequency driven capacitive discharges and that capacitive sheaths can nonlinearly excite driving frequency harmonics near the series resonance that can be spatially near-resonant. The powered-electrode/plasma/grounded-electrode structure of an asymmetrically excited cylindrical discharge forms a three electrode system in which both *z*-symmetric and *z*-antisymmetric radially propagating wave modes exist. We develop a nonlinear electromagnetics model with radially- and time-varying sheath widths, incorporating both modes and plasma skin effects. The discharge is modeled as a uniform density bulk plasma with homogeneous or Child law sheaths at the electrodes, incorporating their nonlinear voltage versus charge relations. The model includes a finite power source resistance and a self-consistent calculation of the dc bias voltages. The resulting set of nonlinear partial differential equations is solved numerically to determine the symmetric and antisymmetric mode amplitudes and the nonlinearly-excited radially-varying harmonics of the two modes. Results are given for a 60 MHz, 10 mTorr chlorine discharge in a 50 cm diameter, 5 cm height chamber with a 30 cm diameter powered electrode.

*Work supported by DOE Fusion Energy Science Contract DE-SC0001939.

14:00

SR3 3 Nonlinear interaction of capacitive discharges and power matching networks FREDERIK SCHMIDT, JAN TRIESCHMANN, RALF PETER BRINKMANN, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum* THOMAS MUSSENBROCK, *Electrodynamics and Physical Electronics Group, Brandenburg University of Technology* External lumped element circuits attached to capacitively coupled plasmas are widely used e.g., in matching networks to maximize the absorbed power. At low pressures the plasma current often consists not only of a single driving-frequency but also of nonlinearly excited harmonics, which have been shown to be of strong influence on the absorbed power and, therefore, the plasma density [1]. The interaction between these harmonics and the external lumped element circuit has to be taken into account in order to achieve maximum power transfer from generator to plasma. For a full understanding of the underlying physics of this coupling a simulation which considers both the plasma and the circuit dynamics can provide useful insights. In this work a method is presented for coupling an equivalent circuit of the plasma to an electrical circuit composed of linear elements modeled with ngSPICE [2]. This is used to investigate the nonlinear interaction of the matching network and capacitive discharges and especially its unexpected influence on the electron heating.

[1]T. Mussenbrock *et al.*, Appl. Phys. Lett. **88**, 151503 (2006).
[2]http://ngspice.sourceforge.net.

14:15

SR3 4 Customizing Capacitively Coupled Plasma Properties with Triple-Frequency Power Sources* CHENHUI QU, PENG TIAN, SHUO HUANG, MARK J. KUSHNER, *University of Michigan* As features sizes continue to shrink, control of reactive fluxes to wafers in capacitively coupled plasmas (CCPs) for semiconductor fabrication must become more precise. To achieve this control, additional frequencies having larger dynamic range are being investigated. In this paper, control of plasma properties in triple-frequency (TF) CCPs is computationally investigated, and compared to dual-frequency (DF) systems. The range of frequencies investigated are a few MHz to 100 MHz, with a standard configuration being two lower frequencies on the bottom electrode, and the high frequency on the top electrode. Electron energy distributions (EEDs) and reactant fluxes to the substrate in process relevant gas mixtures such as $Ar/C_4F_8/O_2$, will be discussed while individually varying the power at different frequencies. The influence of the geometry (e.g., gap spacing and where power is applied) and the consequences of phase off-sets between frequencies in DF and TF systems on EEDs will also be discussed.

*Supported by the NSF, DOE Fusion Energy Sciences and Samsung Electronics.

Invited Papers

14:30

SR3 5 Tailoring charged particle distribution functions and chemical kinetics in non-thermal plasmas using multiple frequency excitation*

A.R. GIBSON, *University of York, UK*

Plasmas driven by multiple frequencies in the radio-frequency range are used extensively in low-pressure plasma processing applications. In recent years, much research has focussed on a particular class of multiple frequency waveform composed of two or more harmonics of a given fundamental frequency with specific phase shifts between them. These are often termed "tailored voltage waveforms". Numerous publications have identified favourable control of ion energy distribution functions (IEDFs), crucial for surface processing applications, in low-pressure plasmas driven by these waveforms. However, the application of tailored voltage waveforms for the optimisation of alternative applications of low-temperature plasmas is less commonly studied. In this contribution, tailored voltage waveforms are explored for the control of the electron energy distribution function (EEDF), key for reactive species production, in atmospheric pressure plasma jets using experimental measurements and numerical simulations. Experimental measurements using phase resolved optical emission spectroscopy (PROES) show that tailoring the shape of the driving voltage waveform through changing the fundamental frequency, number of harmonics, and phase shift between them, has a pronounced effect on the spatio-temporal plasma emission. One-dimensional numerical simulations for the same conditions show excellent agreement with PROES measurements and are used to demonstrate wide ranging control of the EEDF and reactive species production as the shape of the voltage waveform is changed.

*Funding through LABEX Plas@Par ANR-11-IDEX- 0004-02 and UK EPSRC (EP/ K018388/1) is acknowledged.

Contributed Papers

15:00

SR3 6 Investigation of Capacitively Coupled Plasma with electron beam by impedance analysis INSHIK BAE, HONGYOUNG CHANG,* *KAIST* In etching process, one of the key issue is to obtain high self-bias voltage for high ion energy. Therefore dual or triple frequencies Capacitively Coupled Plasma (CCP) has been widely used in etching process. However, if electron beam is added to CCP, the powered plate becomes negatively charged and it brings high self-bias voltage. Therefore we have investigated the dual frequencies CCP with electron beam because of its interesting property. Usually, Langmuir probe is widely used to investigate the plasma but we investigated the CCP with electron beam plasma by impedance analysis instead. The impedance analysis does not affect the plasma and it shows overall circuit characteristics of the plasma. Therefore it has some advantages compared with the Langmuir probe. However, it is not widely used analysis method so we studied the impedance analysis method and compared it with Langmuir probe.

*Academic advisor.

15:15

SR3 7 Experimental evidence of nonlinear standing wave effect excited by higher harmonics in very high frequency capacitive discharges* KAI ZHAO, YONG-XIN LIU, YOU-NIAN WANG, *School of Physics and Optoelectronic Technology, Dalian University of Technology, China* Previous theory and experiment have demonstrated that the standing wave effect in very-high-frequency (VHF) capacitive discharge can cause severe plasma non-uniformity. In this work, the spatial distribution of electromagnetic field in a 100 MHz capacitively coupled argon discharge has been measured utilizing a newly designed high-frequency magnetic probe, combined with a resonance hairpin probe to determine the plasma density. Our results show that the radial profile of plasma density exhibits a center-peaked distribution at 3 Pa, suggesting a pronounced standing wave effect. Observed from the FFT spectra of the magnetic measurement results, it is found that the fundamental frequency component of magnetic field tends to be linear increased with the radial position, whereas its higher harmonic components turn out to be maximum at the positions between the reactor center and the electrode edge. Furthermore, with the increase of the harmonic order, the position corresponding to the maximum magnetic field can be clearly observed to shift toward to the reactor center. These results has demonstrated that the nonuniformity of the plasma density dominated by the standing wave effect could primarily ascribed to the higher harmonics close to the reactor center.

*This work has been supported by the National Natural Science Foundation of China (NSFC) (Grant Nos. 11335004 and 11405018).

SESSION TR1: MAGNETICALLY ENHANCED PLASMA II
Thursday Afternoon, 9 November 2017; Room: Salon D at 16:00; Charter Stinespring, West Virginia University, presiding

Invited Papers

16:00
TR1 1 Particle-in-cell simulations of instabilities in magnetron plasmas*
DENIS EREMIN, *Ruhr-University Bochum*

Magnetron plasma discharges are typically used in sputtering applications, which require low (<1 Pa) neutral gas pressure. This leads to electron mean free path much larger than device size, demanding a kinetic and non-local description. A popular Particle-in-cell (PIC) method employed for this purpose in its simplest variants (explicit or direct implicit schemes) has certain limitations, which encumber its use for 2d and 3d simulations of realistic cases. A novel energy-conserving implicit PIC technique enables simulations of magnetron plasmas with densities up to those observed in high-power impulse magnetron sputtering (HiPIMS) discharges. The corresponding simulations allow studying a number of pending questions concerning magnetron plasma physics. Of special interest are various instabilities arising in such type of plasmas. Leading to the so-called anomalous transport, for example, through the micro-turbulence or large nonlinearly saturated self-organized spoke structures, they are frequently critical for the discharge mere existence. The present talk will discuss observation of various instabilities in 2d and 3d PIC self-consistent simulations in magnetron discharges operated in different regimes.

*This work has been financially supported in the framework of SFB-TR 87 project funded by the German Research Foundation.

Contributed Papers

16:30
TR1 2 Kinetic model of magnetized technological plasma* RALF PETER BRINKMANN, DENNIS KRÜGER, *Theoretical Electrical Engineering, Ruhr-University Bochum* Plasma processes like magnetically enhanced reactive ion etching (MERIE), plasma ion assisted deposition (PIAD), and conventional and high power impulse magnetron sputtering (dcMS/HiPIMS) employ magnetized high density plasmas at relatively low pressures. This regime is very difficult to analyze. Fluid models do not apply and numerical kinetic approaches like particle-in-cell are rather expensive. An alternative may be "gyrokinetics". This theory - actually more a class of theories - was designed and successfully employed in the field of fusion plasmas. It relies on the insight that the fast gyro motion of magnetized particles can be mathematically separated from the slower drift motion and be integrated out, leaving only the dynamics on slower time scales and larger length scales. This contribution will present a gyrokinetic theory for magnetized technical plasmas that is based on first principles. The outset is a general kinetic description of the electron component, the final result is a closed system of parabolic differential equation in just two dimensions.

*DFG via SFB TR 87.

16:45
TR1 3 Analysis of the sheath model for radio frequency magnetron discharges DENNIS ENGEL, LAURA KROLL, DENNIS KRUEGER, RALF PETER BRINKMANN, *Ruhr University Bochum, Germany* Based on a global capacitive radio frequency discharge model [1], a new model for magnetron discharges has been proposed. In this model, the magnetized region is represented by a resistance, taking into account Bohm-diffusion [2]. Due to an asymmetric electrode configuration ($A_{\text{grounded}} \gg A_{\text{powered}}$) different models for the sheath at the electrodes are implemented. The grounded electrode is represented by a DC-floating-potential and for the powered electrode the dynamic behavior of the sheath is regarded. The effects of this assumption to the new, magnetized model are discussed. In the second part of this work, the sheath model itself is considered. It is assumed to be a matrix sheath. Although being a quite simple model, qualitatively good results can be obtained in comparison to experiments. Within the model the ion density is considered to be constant inside the whole sheath region, which is obviously a crude assumption. To improve this, new ion density profiles are implemented. The new voltage-charge ($V(Q)$)-characteristic is determined and the effects on the nonlinear resonance behavior are studied.

[1]T. Mussenbrock *et al.*, PSST **16**, 377 (2007).
[2]D. Bohm, The characteristics of electrical discharges in magnetic fields (1949).

17:00
TR1 4 Microwave Assisted Helicon Plasmas* JOHN MCKEE, DAVID CARON, ANDREW JEMIOLO, EARL SCIME, *West Virginia University* The use of two (or more) rf sources at different frequencies is a common technique in the plasma processing industry to control ion energy characteristics separately from plasma generation. A similar approach is presented here with the focus on modifying the electron population in argon and helium plasmas. The plasma is generated by a helicon source at a frequency f0 = 13.56 MHz. Microwaves of frequency f1 = 2.45 GHz are then injected into the helicon source chamber perpendicular to the background magnetic field. The microwaves damp on the electrons via X-mode Electron Cyclotron Heating (ECH) at the upper hybrid resonance, providing additional energy input into the electrons. The effects of this secondary-source heating on electron density, temperature, and energy distribution function are examined and compared to helicon-only single source plasmas as well as numeric models suggesting that the heating is not evenly distributed. Optical Emission Spectroscopy (OES) is used to examine the impact of the energetic tail of the electron distribution on ion and neutral species via collisional excitation. Large enhancements of neutral spectral lines are observed in both Ar and He. While small enhancement of ion lines is seen in Ar, ion lines not normally present in He are observed during microwave injection.

*U.S. National Science Foundation Grant No. PHY-1360278.

17:15

TR1 5 Electron Drift Dynamics at the Plasma Boundary Sheath in Magnetized Low Temperature Plasmas* DENNIS KRUEGER, JAN TRIESCHMANN, RALF PETER BRINKMANN, *Ruhr University Bochum, Germany* Two important examples of magnetized low temperature plasmas are high power impulse magnetron sputtering (HiPIMS) and Hall-effect thrusters. Although being designed for completely different applications, similar features can be identified. Common electric and magnetic field configurations lead to various types of drifts and instabilities. One peculiar phenomenon in such discharges are rotating patterns, sometimes called spokes, which develop under certain discharge conditions. As self-organized symmetry breaking structures, these patterns can only be understood by 3d models. To formulate a consistent 3d model, an appropriate boundary condition at the plasma walls must be utilized. Therefore, we investigate the interaction of magnetized electrons with the plasma boundary sheath by means of a 3d kinetic single electron model. For two different sheath models, a specular reflection model and a more physical Bohm sheath model, we find that the effective outcome, in particular the resulting drifts of the guiding center, are very similar.

*This work is supported by the German Research Foundation in the frame of the Collaborative Research Center TRR 87.

SESSION TR2: DISSOCIATION, RECOMBINATION, AND ATTACHMENT
Thursday Afternoon, 9 November 2017; Room: Duquesne at 16:00; Rainer Johnsen, University of Pittsburgh, presiding

Invited Papers

16:00

TR2 1 Electron/molecular cation collisions in low-temperature plasmas: from mechanisms to rate coefficients*
IOAN F. SCHNEIDER, *LOMC CNRS-UMR6294, Le Havre University*

The kinetics of various cold ionized media is driven by electron-impact dissociative recombination, dissociative excitation and ro-vibrational (de)excitation of molecular cations [1]. These collisions are highly reactive, involve numerous super-excited molecular states undergoing predissociation and/or autoionization, and their measurement and modeling both result in cross sections desplaying a strong resonant character. Their theoretical study requires sophisticated methods capable to go far beyond the Born-Oppenheimer approximation, and to manage to describe a complex molecular dynamics relying on the superposition of many continua and infinite series of Rydberg states. We have used the Multichannel Quantum Defect Theory (MQDT) in order to compute cross sections and rate coefficients for the invoked processes for H_2^+, H_3^+, N_2^+ [2], BeH^+ [3], BF^+, NO^+, CO^+, SH^+, CH^+ and ArH^+, and we have compared them with the experimental ones - obtained in storage rings and flowing afterglows.

*Collaborators: J. Zs. Mezei, Paris 13 Univ., F. Colboc, Y. Moulane, V. Laporta, Le Havre Univ., D. A. Little, J. Tennyson, UCL, M. D. Epee, O. Motapon, Douala Univ., S. Niyonzima, Burundi Univ., N. Pop, Timisoara Univ., K. Chakrabarti, Calcutta Univ..

[1] I. F. Schneider, O. Dulieu, and J. Robert (eds.), Eur. Phys. J. Web Conf. **84** (2015).
[2] D. A. Little *et al.*, Phys. Rev. A **90**, 052705 (2014).
[3] V. Laporta *et al.*, Plasma Phys. Contr. Fusion **59**, 045008 (2017).

16:30

TR2 2 Kinetics of transient species with cations and electrons*
NICHOLAS SHUMAN, *Air Force Research Laboratory*

Weakly ionized plasma will generally contain some concentrations of transient species, e.g. small fluorocarbon radicals in a discharge through CF_4. Experimental measurements of the kinetics of these species with electrons and with ions are scarce in the literature, in part due to the difficulty in producing and quantifying transient species. We have developed a technique, termed variable electron and neutral density attachment mass spectrometry (VENDAMS), employing a flowing afterglow-Langmuir probe apparatus that provides access to the kinetics of a wide range of radical or otherwise unstable species reacting with electrons or with cations. The kinetics of electron attachment to small fluorocarbon and hydrofluorocarbon radicals have been measured at thermal conditions from 300–1000 K. The results are interpreted using a kinetic modeling approach rooted in statistical theory, which allows extrapolation of the results to conditions not accessible by the experiment, including to extreme temperatures, pressures, or non-thermal conditions. The ion-molecule kinetics of small hydrocarbon, fluorocarbon, and hydrofluorocarbon radicals with a number of cations were also studied under thermal conditions. Surprisingly, the radical species react less efficiently and with a lower likelihood of long-range charge transfer than similar reactions of stable, closed-shell species with the same cations. The VENDAMS technique is also used to study ion-ion mutual neutralization processes. The rate coefficients of mutual neutralization in systems involving greater than 3 atoms vary by no more than about a factor of 5. On the other hand, the rate coefficients of mutual neutralization of two atomic species can vary widely. In some systems the rate coefficients are of similar magnitude to those for polyatomic species, but in other cases at least 2 orders of magnitude smaller. A large number of measurements are distilled down to a simple parametrization to predict the rate coefficients of unstudied systems.

*Work supported through Air Force Office of Scientific Research; AFOSR-RV16COR276.

Contributed Papers

17:00

TR2 3 Development of DEA instrumentation for a comprehensive understanding of gas-phase molecular fragmentation* SYLWIA PTASINSKA, ZHOU LI, ALEKSANDAR R. MILOSAVLJEVIC, IAN CARMICHAEL, *University of Notre Dame* Electron attachment to a molecule triggers several dissociation pathways of transient molecular anions, each resulting in the formation of one negative ion and its counterpart. The counterpart can be a single neutral radical or several fragments. However, there are no studies that detect the neutrals formed from the dissociative electron attachment (DEA) process to molecules in the gas phase. In order to do this, we developed stepwise electron spectroscopy (SWES) [1]. We detected the neutrals produced upon DEA to CCl_4 at ~0 eV by measuring the appearance energies of CCl_3 radical as well as the other neutral species. In addition, we combined the experimental findings with high-level quantum chemical calculations to obtain a complete analysis of both the DEA to CCl_4 and the subsequent electron-impact ionization of CCl_3 radicals. The detection of neutral radicals can be essential from the point of view of radiation damage to DNA, particularly in the case of double strand breaks (DSBs) by low energy electrons [2].

*This work is supported by the U.S. Department of Energy Office of Science, BES (DE-FC02-04ER15533).

[1]Z. Li *et al.*, Phys. Rev. Lett. (2017) in press.
[2]B. Boudaiffa *et al.*, Science **287**, 1658 (2000).

17:15

TR2 4 Contrast between electron attachment to CH_3SCN and CH_3NCS* THOMAS M. MILLER, NICHOLAS S. SHUMAN, ALBERT A. VIGGIANO, *Air Force Research Laboratory* We have made measurements of electron attachment to CH_3SCN (methyl thiocyanate) and CH_3NCS (methyl isothiocyanate) over the temperature range 300–1000 K in a flowing afterglow Langmuir probe apparatus. Both attachment processes yield mainly the SCN^- pseudohalide anion product. Both molecules are inefficient at attaching electrons, with the rate coefficient k_a for CH_3SCN near 2×10^{-10} $cm^3\ s^{-1}$ at 300 K and that for CH_3NCS orders of magnitude lower and unmeasurable. Both rate coefficients increase strongly with temperature. The k_a for CH_3SCN is 100 times larger at 1000 K, while k_a for CH_3NCS reaches 4×10^{-9} $cm^3\ s^{-1}$ at 1000 K. Calculations of potential energy surfaces imply that the electron attachment mechanisms are completely different. Attachment to CH_3SCN requires vibrational excitation, but then dissociation of the parent anion readily follows. Formation of the transient CH_3NCS^- anion appears to be more facile, but the dissociative surface has a rate-limiting barrier. The formation of a CN^- anion product is calculated to be 0.5 eV endothermic from CH_3SCN or 0.7 eV from CH_3NCS at 0 K. CN^- appears faintly in the product mass spectra for CH_3NCS, which could be due to impurities, but appears more strongly for CH_3SCN as temperature increases, which is less easily explained. We also have results for C_2H_5SCN, which attaches electrons similarly to CH_3SCN at 300 K, but is 3 times less efficient at 1000 K.

*Supported by Air Force Office of Scientific Research (AFOSR-2303EP).

SESSION TR3: BIOMEDICAL PLASMAS

Thursday Afternoon, 9 November 2017; Room: Oakmont Junior Ballroom at 16:00; Mounir Larossi, Old Dominion University, presiding

Invited Papers

16:00

TR3 1 Therapy and decontamination by plasma sources*

KLAUS-DIETER WELTMANN, *Leibniz Institute for Plasma Science and Technology (INP Greifswald)*

Nowadays cold atmospheric pressure plasmas (CAP) with temperatures below 40 °C offer new therapeutic possibilities. The interest in using plasma sources operating at atmospheric pressure is of increasing importance in life sciences. Plasma Medicine includes already established or applications in progress of gas discharge plasmas, such as the antimicrobial treatment (decontamination) of medical devices, pharmaceutical products or packaging materials as well as surface modification of implants (functionalization, coating) and furthermore different therapeutic applications. Consequently, practical application of CAP in medicine is currently focused on dermatology as well as plastic and aesthetic surgery and oncology. Much basic research is still required to fully understand the complex mechanisms concerning the effects of plasmas on living cells and living tissue for avoiding side effects and identifying systematic treatment options. Whereby topics such as clean air, clean water and clean food are gaining more and more attention. Nevertheless, future application in other fields are expected. Besides treatment of teeth and implants with different purposes, in dentistry also wounds as well as infective and inflammatory diseases of gum and oral mucosa will be targets of CAP application. An overview about present plasma based devices in medicine in different application areas will be given followed by actual results achieved for wound healing and tumor treatment in different hospitals.

*In collaboration with: Thomas von Woedtke, Torsten Gerling, Jürgen Kolb from Leibniz Institute for Plasma Science and Technology (INP Greifswald) and Hans-Robert Metelmann from Greifswald University Medicine, Greifswald, Germany.

Contributed Papers

16:30

TR3 2 Multi-pulse operation of an atmospheric-pressure plasma jet onto a reactive liquid layer* SETH A. NORBERG, *US Military Academy* GUY PARSEY, STUART DAUDLIN, AMANDA M. LIETZ, ERIC JOHNSEN, MARK J. KUSHNER, *University of Michigan* Medical applications of non-thermal atmospheric plasmas are predominantly associated with modification of a liquid environment surrounding tissue. The plasma-induced biological response results from reactive oxygen and nitrogen species (RONS), either produced in the liquid-phase or transferred through solvation from the gas-phase, reaching the target tissue. In atmospheric pressure plasma jets (APPJs), the pulse repetition frequency (PRF) and proximity of the ionization wave to the liquid surface, controlled indirectly through pulse duration, stand out as parameters that can be adjusted to achieve the desired outcome. An APPJ incident onto tissue with an intervening reactive liquid layer was simulated using a 2-dimenstional plasma hydrodynamics model while varying the PRF and plasma-liquid proximity. A high PRF allows for plasma activated species to co-exist in the gas phase for multiple pulses resulting in increasing densities of N_xO_y and hence aqueous NO_3^- and $ONOO^-$. Conversely, a lower PRF minimizes inter-pulse reactions in the gas phase which consume ROS, resulting in a higher ROS fluence to the underlying tissue. The altered reaction pathways are not linear with the PRF as aqueous H_2O_2 fluences to the tissue are not sensitive to PRF variation. Significantly different ratios of fluences of reactive species to the tissue occur when comparing touching and non-touching interaction of the plasma-plume and liquid surface.

*Supported by NSF and DOE Office of Fusion Energy Science.

16:45
TR3 3 Effects of Gas Temperature in Plasma Layer on RONS generation in Array-type Dielectric Barrier Discharge at Atmospheric Pressure* SUNG-YOUNG YOON, CHANGHO YI, SNGHEUM EOM, SEUNGIL PARK, SEONG BONG KIM, SEUNGMIN RYU, SUNG JAE YOO, *Plasma Technology Research Center of National Fusion Research Institute* In this work, we demonstrate the changing of the major plasma generating species under the fixed discharge gas composition. The atmospheric pressure plasmas in the atmosphere are able to produce various reactive oxygen and nitrogen species (RONS). The O_3 and NO_x are representative RONS. Since the influences of these species show different influences on the organisms, it is necessary to change the plasma produced species depending on the treatment targets. We generate the plasma under ambient airflow using the array-type dielectric barrier discharge (DBD) electrode. The plasma generated species with flow rates are monitored using the FTIR. It was found that main generation transits from O_3 to NO_x as the flow rate increased. As a result of comparative analysis by measuring the gas temperature in discharge and the electrode surface temperature using OES and IR, it was found that the gas temperature of the discharge layer is an important factor to regulate the discharger species.

*This study was supported by R&D Program of 'Plasma Advanced Technology for Agriculture and Food (Plasma Farming)' through the National Fusion Research Institute of Korea (NFRI) funded by the Government funds.

Invited Papers

17:00
TR3 4 Plasma jets and electric fields delivery on targets relevant for biomedical applications
ERIC ROBERT, *GREMI, CNRS/Universite d'Orleans*

The study of plasma jets operating in free jet mode and on conductive targets relevant for biomedical applications is discussed. The simultaneous diagnostics of helium metastable through laser absorption, electric field (EF) with an electro-optic probe and current appears as a unique approach to get deep insights on the mechanisms triggered when primary ionization wave (IW), driving the plasma jet propagation, impacts the target. Secondary IWs, back and forth travelling from the plasma jet powered electrode and the grounded target, is measured and may result, depending on the operating parameters of the device, in the transition to a glow like discharge. In such situation, huge enhancement of reactive species production is triggered in connection with significant increase of current flowing through the target. This study allow for a better analysis of the plasma jet delivery on target relevant for biomedical applications and open up opportunities to control reactive species concentration and current amplitude in such experiments. These experimental results are in good agreement with modeling work recently published by group of M.J. Kushner (University of Michigan) on the plasma jet touching or not targets of various natures. The second aspect of the study deals with the characterization of both the amplitude and the topology of the transient EF generated in the vicinity of the plasma jets. Time resolved longitudinal and radial EF, with respect to the jet propagation axis, having amplitudes ranging from a few to a few tens of kV/cm have been measured. There also a good agreement is achieved with modeling data from the group of A. Bourdon (LPP laboratory) which allow extending this diagnostics to region where experimental analysis is hard or disturbing with our probe. It is probably worth considering such intense EF with respect to their potential impact on biological samples.

SESSION UR1: RECEPTION AND BANQUET
Thursday Evening, 9 November 2017; Room: Salon ABC at 18:30;

18:30
UR1 1 Reception and Banquet

SESSION VF1: NANOPARTICLES
Friday Morning, 10 November 2017
Room: Salon D at 8:00
Koichi Sasaki, Hokkaido University, presiding

Contributed Papers

8:00

VF1 1 Effect of the electrostatic interaction in the coagulation of nanoparticles in argon-silane plasma simulations BENJAMIN SANTOS, FRANÇOIS VIDAL, LAURA CACOT, CLAUDE BOUCHER, *INRS - Energie et Materiaux* It is known that nanoparticles in low-temperature plasmas are mostly charged negatively. Recently Mamunuru *et al.* [1], pointed out the existence of positively charged and neutral nanoparticles. This possibility promotes the coagulation because of the Coulomb interaction enhancement between particles of opposite charge. Moreover, Ravi *et al.* [2] studied the coagulation enhancement between neutral and charged nanoparticles, which is due to the image potential. In this work, we extended the study on the effects of the electrostatic interaction between nanoparticles on particle growth in an argon-silane low-temperature plasma. For this purpose, we developed a computer simulation based on the general dust-plasma self-consistent model established by the Girshick's group [3], but we use a more rigorous approach, which includes polarization induction for calculating the electrostatic force between dielectric particles. It is shown that the coagulation is enhanced in neutral-charged particles encounters but in a lesser way than the previous study. Detailed results will be discussed during presentation.

[1]Mamunuru *et al.*, Plasma Chem Plasma Process **37**, 701 (2017).
[2]Ravi *et al.*, Phys. Rev. E **79**, 26408 (2009).
[3]Plasma Chem Plasma Process **34**, 1 (2013) and references therein.

8:15

VF1 2 Effect of Vaporization on Aerosol Dynamics in Low Temperature Dusty Plasmas NECIP UNER, ELIJAH THIMSEN, *Washington Univ* Low temperature dusty plasmas (LTDP) are known to display a wide range of emergent phenomena due to the complex interactions between particles and the plasma. Some of the unique properties of dusty plasmas, such as suppressed coagulation and particle heating, have been successfully utilized for synthesizing monodisperse nanoparticles of various materials with high crystallinity. The general conception of nanoparticle growth involves nucleation due to the rapid conversion of gaseous precursors, which is followed by surface growth. Coagulation is effectively suppressed if the particle concentration is lower than the ion density, due to electrostatic interactions between negatively charged nanoparticles. The absence of reports on the synthesis of metal particles suggests that there may be additional dynamics occurring in LTDP. By sending premade aerosols into a radio frequency argon plasma, we demonstrate that metal particles can vaporize in the LTDP, despite the low gas temperature. Due to the nonequilibrium vaporization process unique to LTDP, a monodispersed aerosol was found to emerge from a polydispersed aerosol. A theoretical model for the evolution of the size distribution will be presented along with experimental results for several materials.

8:30

VF1 3 Investigation of Wear-resistant Enhancement of Polyurethane Composite Film with Plasma-treated Carbon-nanotubes DAISUKE OGAWA, *None* KAZUKI MICHIYA, HIDEO UCHIDA, KEIJI NAKAMURA, *Chubu University* Our former results showed that the plasma-treated CNTs enhanced the wear-resistance of polyurethane (PU) by means of making a CNT composite film. In particular, a treatment with the plasma made from a gas mixture of nitrogen and carbon dioxide was the most effective to enhance the wear-resistance. We have not understood the mechanism of the enhancement yet, but speculating two possibilities for the enhancement. The first possibility is due to a physical effect, in which the plasma treatment somehow enhances more uniform and more mono-sized distribution of CNTs in a PU film. The second possibility is due to a chemical effect. According to the discharge condition, nitrogen, carbon and oxygen species in the plasma can create isocyanate groups (R-NCO) on the CNTs. In fact, isocyanate groups can harden PU through chemical reactions. In order to find the main cause of the enhancement, we first observed the film with an optical microscope. However, the observation showed that the distribution of CNTs treated with the plasma was almost the same as that of other CNTs. On the other hand, the other investigation with acridine yellow, which is an indicator of the isocyanate groups through fluorescence, showed more isocyanate groups on the CNTs treated with the plasma.

8:45

VF1 4 Self-consistent numerical simulation of carbon transport in the arc discharge for carbon nanotube synthesis* ALEXANDER KHRABRY, ANDREI KHODAK, *Princeton Plasma Physics Laboratory, Princeton, NJ* KENTARO HARA, *Texas A & M University, College Station, TX* VALERIAN NEMCHINSKY, *Keiser University, Fort Lauderdale, FL* IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory, Princeton, NJ* In carbon nanotube synthesis in the arc, graphite anode ablates providing carbon material into the arc core. Most of the carbon material deposits onto a surface of cathode, whereas some part of it escapes from the inter-electrode gap, cools down and serves as a feedstock for growth of nanoparticles. Carbon atoms associate into carbon dimers, trimmers, etc. with the dimers being the main precursor for growth of carbon nanotubes. Ablation rate is very sensitive to such arc parameters as arc current and gap width. Numerical simulations of carbon arc were performed using self-consistent model which couples effects of fluid flow, carbon transport, current flow, and heat transfer in both plasma and electrodes. Plasma model accounts for non-equilibrium conditions in the arc including effects of space-charge sheaths and solves separate transport equations for ion and neutral species. The arc model was implemented into general-purpose CFD-code ANSYS CFX, which was highly customized for this purpose. Very good agreement between simulation results and experimental data [1] on ablation/deposition rates and density profile of carbon dimers were obtained.

*Research supported by the U.S. Department of Energy (DOE), Office of Science, Fusion Energy Sciences (FES).

[1]V. Vekselman *et al.*, Plasma Sources Sci. Technol. (2017).

9:00

VF1 5 On the Structure Control of Vertical Nanographene Network MINEO HIRAMATSU, HITOSHI NOZAKI, TAKUYA SUZUKI, KEIGO TAKEDA, *Meijo University* HIROKI KONDO, MASARU HORI, *Nagoya University* Carbon nanowalls (CNWs) are few-layer graphenes, standing vertically on a substrate to form a self-supported network of wall structures. The maze-like architecture of CNWs would be useful as a platform for electrochemical and bio-sensing, and energy conversion, due to the large surface area of conductive carbon and the wide capability of surface modification including decoration with metal nanoparticles. CNWs can be fabricated using PCVD. The balance between carbon precursors and etching radicals would affect the morphology, crystallinity and growth rate of CNWs. For example, H content in the plasma increased, crystallinity improved and interspaces between adjacent nanowalls increased, while the growth rate of CNWs decreased. From a practical point of view, control of CNW structures including spacing between adjacent nanowalls and crystallinity is significantly important, and their nucleation control should be crucial, since the basic structure would be determined by the nucleation. We carried out CNW growth using PCVD employing $CH_4/H_2/Ar$ mixture with emphasis on the structure control of CNWs. In this work, we report the effects of ion bombardment and catalytic metals on the nucleation of vertical nanographenes to realize active control of interspace between adjacent walls.

9:15

VF1 6 Nanoparticle formation from HMDSO in an atmospheric pressure plasma jet* ROGER WALLIMANN, GINA OBERBOSSEL, DENIS BUTSCHER, PHILIPP RUDOLF VON ROHR, *ETH - Zurich* Nanoparticles are admixed to fine powders to enhance their flowability. In industry, this is mostly done in time consuming batch processes. As an alternative which could be used in a continuous process, the silica nanoparticle formation in plasma was investigated. For nanoparticle formation, HMDSO, argon and oxygen were used in an atmospheric pressure plasma jet powered by a sinusoidal high voltage generator. Oxygen levels, gas flow and frequency were varied to find optimal particle production conditions. The particles were collected using an electrostatic precipitator. HMDSO dissociation and conversion was determined by weight measurements of the precipitator tube. Particles were analyzed using FTIR and SEM to attain their composition and size, respectively. Conversion rates were in the range of 3 to 10%. Below a frequency of 70 kHz, only film formation occurs since most of the nuclei are lost on the channel walls. Optimal oxygen levels for maximum yield was shown to be 2.5%, below and above, dissociation was limited by power input and plasma quenching, respectively. Particle size was in the range of 30-60 nm and increased slightly with decreased volume flow. The composition of the films and particles were silica-like with a low amount of carbon.

*Gebert Ruef Stiftung, Fondation Claude et Giuliana.

SESSION VF2: GAS PHASE PLASMA CHEMISTRY II
Friday Morning, 10 November 2017
Room: Duquesne at 8:00
David Staack, Texas A&M University, presiding

Contributed Papers

8:00

VF2 1 Plasma chemistry model of microdischarge in flowing humid air directly heated by discharge* CHANGHO YI, SUNGYOUNG YOON, SANGHEUM EOM, SEUNGIL PARK, SEONG BONG KIM,† SEUNGMIN RYU, SUK JAE YOO, *Plasma Technology Research Center, National Fusion Research Institute* We present a numerical model of microdischarge in humid air of atmospheric pressure considering the effects of direct ohmic heating of discharge layer and heat and particle transport by flow. The model consists of three coupled well-mixed regions of hot discharge layer, warm afterglow layer, and cold large volume layer, which interact with each other through thermal conduction, diffusion, and particle flow. The calculated results and experimental results of Fourier transformed infrared absorption spectroscopy shows reasonable agreements for dynamics of various reactive oxygen and nitrogen species, and showed large discrepancy when ohmic heating in discharge layer was ignored. These results indicate that localized ohmic heating by microdischarge substantially affected on the chemical reactions with temperature dependence. Heat and particle transport by flow also affected on dynamics of reactive neutral species in various gas flow configurations. Hence, the deposition and transfer of both heat and species should be considered together to properly calculate the dynamics of reactive neutral species in microdischarges.

*This study was supported by Research and Development Program of 'Plasma Advanced Technology for Agriculture and Food (Plasma Farming)' through the National Fusion Research Institute of Korea (NFRI) funded by the Government funds.
†Corresponding author (sbkim@nfri.re.kr).

8:15

VF2 2 Efect of discharge tube temperature on the densities of $N_2(A^3\Sigma_u^+)$ and atomic nitrogen in a remote nitrogen plasma source MASAHARU SHIMABAYASHI, *Hokkaido Univ.* KAZUAKI KURIHARA, *Toshiba/Imec* KOICHI SASAKI, *Hokkaido Univ.* We investigate the application of a remote nitrogen plasma source to the surface nitriding of SiC. In this work, we tried the control of the densities of reactive nitrogen species ($N_2(A^3\Sigma_u^+)$ and atomic nitrogen) by the temperature of the discharge tube. The remote nitrogen plasma was produced using a microwave resonator (2.45 GHz) which was installed on the outside of a discharge tube with an inner diameter of 8 mm. The microwave resonator was located at a distance of 7-16 cm from the measurement position. A part of the discharge tube between the resonator and the measurement position was heated up to 600 °C by applying a heating power to a kanthal spiral wire on the outside of the discharge tube. We observed the slight increase (several tens of percent) in the density of atomic nitrogen by the discharge tube heating. On the other hand, the density of $N_2(A^3\Sigma_u^+)$ decreased significantly (an order of magnitude) with the discharge tube temperature. These results indicate that the high temperature of the discharge tube affects the loss frequencies of atomic nitrogen and $N_2(A^3\Sigma_u^+)$ oppositely.

8:30

VF2 3 Sensitivity analysis and uncertainty quantification for the electric field determination in air from FNS and SPS ratio* ZDENEK BONAVENTURA, PETR BILEK, ADAM OBRUSNIK, TOMAS HODER, *Masaryk University, Fac. Sci., Dept. Phys. Electronics., Czech Republic* MILAN SIMEK, *Dept. Pulse Plasma Systems, IPP, The Czech Academy of Sciences, Czech Republic* Frequently used method for the determination of the electric field in discharges in air is based on the measurement of the ratio of luminous intensities emitted by radiative states of $N_2(C^3\Pi_u)$ (second positive system) and $N_2^+(B^2\Sigma_u)$ (first negative system This method is used for wide range of pressures from ground pressures, where it is applied for example to investigation of dielectric barrier discharge, up to ionospheric altitudes for remote sensing of Transient Luminous Events, e.g., lightnings, sprites and blue jets. It is well know that quenching rates of $N_2(C^3\Pi_u)$ and $N_2^+(B^2\Sigma_u)$ determined by various experimental methods exhibit serious discrepancies. Therefore we aim to investigate the impact of uncertainties in values of these rates on the electric field determined from FNS/SPS ratio. We present uncertainty quantification and sensitivity analysis for the kinetic scheme for resulting ratio of the FNS and the SPS. This analysis is based on the Elementary Effects (EEs) method invented by Morris. Uncertainty quantification based on Monte Carlo methods will be applied.

*This research has been supported by the Czech Science Foundation research project 15-04023S.

8:45

VF2 4 OH generation in a pulsed He plasma jet with water electrode* SHUTONG SONG, CHUNQI JIANG, *Frank Reidy Center for Bioelectrics Old Dominion University* The highly reactive hydroxyl radicals play a key role in various biomedical applications such as surface decontamination, wound disinfection and cancer treatment. This study investigated a needle-electrode pulsed helium plasma jet interacting with a water-covered ground electrode via electrical model and optical emission spectroscopy. The helium plasma jet driven by 6 kV pulses with varied pulse duration at 1 kHz was generated and impinged onto the water surface with an inter-electrode gap of 10 mm. An equivalent circuit, composed of a 6.3 pF capacitor which represented the capacitive jet device and in parallel with an adjustable resistor and capacitor in series for the plasma plume, can be used to model the plasma system based on the voltage-current waveforms. Optical emission spectroscopy revealed that total OH intensity along the plume increased with longer pulse duration in a range from 200 ns to 900 us. However, the OH energy yield, indicating the energy efficiency of OH production, is the highest at a pulse duration of 800 ns and 7.5 times higher compared to the second-highest at 900 us. Plume temperature were measured at different pulse durations and are further discussed assisted with modeling of OH ($A^2\Sigma$-$X^2\Pi$) emission spectra.

*Air Force Office of Scientific Research Award Number FA9550-17-1-0257.

9:00

VF2 5 Chemical Kinetics Mechanisms Study of High Electron Density Argon-Water Filamentary Discharges* YUCHEN LUO, *University of Minnesota* AMANDA LIETZ, MARK KUSHNER, *University of Michigan* PETER BRUGGEMAN, *University of Minnesota* Although the plasma kinetics of He-H_2O mixtures has been investigated for diffuse low electron density atmospheric pressure glow discharges, the kinetics of high electron density filamentary discharges is less well known. In this work, we study the kinetics of a filamentary nanosecond pulsed Ar+0.26% H_2O plasma using a 0D chemical kinetics model with comparison to previously measured OH and H densities by time resolved laser induced fluorescence (LIF) and two-photon absorption LIF [1]. Good agreement is obtained for absolute values of the H and OH densities. There are, however, discrepancies between the model and the experiment and the origin of these discrepancies will be discussed. Results from the model indicate that the production of H/OH involve electron dissociative recombination reactions with water ions and its clusters. H and OH consumption in the afterglow are due to radical-radical recombination. The significantly lower density of OH compared to the H density is due to electron induced dissociation of OH during the discharge pulse and enhanced recombination by the large O density in the afterglow. Effects of air impurities, local depletion of water at the filament position and transport on the OH kinetics will also be discussed.

*This work was supported by NSF (PHY 1500135) and the DOE (DE SC0001939).

[1]Yatom *et al.* (submitted).

9:15

VF2 6 Spatially Resolved Ozone Density in Volumetric and Surface Dielectric Barrier Discharges via Absorption Spectroscopy* RYAN T. SMITH, BJÖRN OFFERHAUS, FRIEDERIKE KOGELHEIDE, NIKITA BIBINOV, PETER AWAKOWICZ, *Allgemeine Elektro- und Plasmatechnik Ruhr-UniversitÃ¤t Bochum* KATHARINA STAPELMANN,† *Nuclear Engineering - North Carolina State University* Absorption spectroscopy is performed on two different Dielectric Barrier Discharges, a Surface (SDBD) and a Volumetric (VDBD), in order to measure the Ozone (O_3) density within the gas phase. A Laser Driven Light Source (LDLS) is used as a very stable, high intensity broad-band source between 170 nm and 2400 nm. The light emitted from the collimated LDLS and the plasma are shown through a narrow band filter at 253.7 ± 5 nm to isolate the O_3 Hartley band centered about 253.65 nm. Absorption measurements are performed on both the SDBD and VDBD at atmospheric pressure under varying gas mixtures and at flows of 10 slm and 2 slm, respectively. Spatial resolution is achieved on the order of 0.1 mm with a CCD camera. Furthermore, measurements are taken at multiple frequencies and peak to peak voltages resulting in varying power densities. A direct comparison of the gas phase O_3 is made at the same operating frequency and power density of the two plasma sources.

*SFB-TR 87/2.

†Also affiliated with Allgemeine Elktro- und Plasmatechnik Ruhr-Universität Bochum.

SESSION VF3: SURFACE TREATMENT AND DEPOSITION
Friday Morning, 10 November 2017
Room: Oakmont Junior Ballroom at 8:00
Eva Kovacevic, Universite d'Orleans, presiding

Contributed Papers

8:00

VF3 1 Improvement of thin films by plasma assisted deposition EDMUND SCHUENGEL, SILVIO GEES, SILVIA SCHWYN-THOENY, *Evatec AG, 9477 Truebbach, Switzerland* The quality of thin films deposited in sputter processes is improved by using an additional plasma treatment. Here, the role of an additional capacitively coupled radio frequency plasma with a single grid confinement is investigated. We focus on the scenario of the sputter plasma and the plasma source being active at the same time in the same vacuum environment, with a substrate repeatedly being exposed to either one of them. Depending on the conditions, the additional treatment by the plasma source may affect the deposition process physically by generating energetic ions, which bombard the surface, and chemically by generating reactive species such as atomic oxygen. A significant interaction between the dc or dcrf sputter plasma, where the reactive gas flow is actively controlled, and the auxiliary rf plasma is observed. These effects are examined by voltage and ion energy measurements as well as by optical emission spectroscopy. Furthermore, the benefits in film structure, surface roughness, and optical properties due to physical and chemical mechanisms in plasma assisted processes are highlighted.

8:15

VF3 2 Dielectric barrier discharges prevent cracking in hard latex dispersion coatings SEBASTIAN DAHLE, THOMAS WATERS, WOLFGANG MAUS-FRIEDRICHS, *Clausthal University of Technology* The deposition of coatings from latex dispersions is commonly used in various industrial and commercial fields. Most of these paints use acrylate or methacrylate copolymers, since these are well resistant against weathering, UV and many chemicals. However, the hardest copolymers, which offer the highest abrasion resistances and mechanical stabilities, suffer from a cracking that is hard to prevent. Many elaborate approaches try to circumvent this behavior, which is known as the film formation dilemma. By applying a dielectric barrier discharge, in air, on to the wet film for short periods of time, we were able to prevent the latex film from cracking. Even though the physical effects of the plasma treatment, such as an increased drying rate and a slight temperature increase, did influence the film formation, the observed effect appears to be mostly caused by chemical changes in the surface layer.

8:30

VF3 3 Plasma based synthesis of conductive polymer nanostructures: from nanoparticles to thin films* JOHANNES BERNDT, CEDRIC PATTYN, *GREMI CNRS&University of Orleans* ANA DIAS, *Técnico Lisboa - Universidade de Lisboa* EVA KOVACEVIC, *GREMI CNRS&University of Orleans* This contribution deals with polymerization processes in aniline containing low temperature plasmas. The work is focused on the synthesis of conductive polymers which are produced either as thin films (deposited on advanced nanocarbons like carbon nanotubes, carbon nanowalls and graphene) or as nanoparticles. The work will discuss some general strategies for the plasma based synthesis of conductive polymers (based on plasma and material diagnostics as for example in-situ FTIR, mass spectroscopy, etc) and will give as well some examples for applications.

*The authors acknowledge the support of French Research Agency via ANR project PlasBioSens and French Region Centre for their support via the project APR Capt'Eau. The author would like to acknowlegde also support for A.D via programme APPLAuSE.

SESSION WF1: RECONFIGURABLE AND INTERACTING PLASMAS

Friday Morning, 10 November 2017; Room: Salon D at 10:00; Katharina Stapelmann, North Carolina State University, presiding

Invited Papers

10:00

WF1 1 Plasmas for Reconfigurable Radio-Frequency Systems*

SERGEY MACHERET, *Purdue University, School of Aeronautics and Astronautics*

The presentation discusses properties of weakly ionized plasmas from the standpoint of their potential application to tunable and reconfigurable radio-frequency (RF) electronics: antennas, resonators, filters, limiters etc. Plasmas have important advantages in comparison with other (e.g. semiconductor, ferrite etc.) solutions, especially in high-power regimes. Although the RF applications motivate the plasma research, the focus of this presentation is on the relevant fundamental aspects. First, we show that plasmas can combine resistive, capacitive, and inductive properties and that all three can be tuned over very wide ranges. We then discuss recent proof-of-principle experiments on using simple gas discharges as tunable elements in resonant LC filters, resonators, and limiters. We then turn to plasma antennas and show that such antennas generally have lower gain than metallic antennas do, but the cross-coupling between different elements of an array is also lower, which is an important plasma advantage. Finally, we discuss the critical problem of Johnson-Nyquist noise and show that although conventional plasma antennas can be very "noisy", sustaining the plasma by nanosecond repetitive pulses could enable low-noise plasma antennas.

*Abbas Semnani and Dimitrios Peroulis (Purdue University, School of Electrical and Computer Engineering) are co-authors of this work. This work was funded in part by the National Science Foundation.

Contributed Papers

10:30

WF1 2 Plasma Photonic Crystals using Arrays of Microplasma Jets Devices HEE JUN YANG, JINHONG KIM, SUNG-JIN PARK, J. GARY EDEN, *Univ of Illinois - Urbana* Photonic crystals composed of microplasma and air can be made with arrays of microplasma jets devices. Compared to the solid-state photonic crystals, plasma photonic crystals are reconfigurable at electronic speeds. Also, both spatial period and refractive index can be controlled in plasma photonic crystals. Diameter of each microplasma jet is 400 μm and pitch to pitch distance is 1 mm and operated in He gas flow. With a distributed Bragg reflector (DBR) structure with periodicity of 1 mm, attenuation of wave occurs at 150 GHz. Calculations and characteristics of plasma photonic crystals will be discussed. Two-dimensional microplasma photonic crystals at 157 GHz have been demonstrated.

10:45

WF1 3 Multiscale numerical modeling in plasma metamaterial systems* DYLAN PEDERSON, KONSTANTINOS KOURTZANIDIS, LAXMINARAYAN RAJA, *The University of Texas at Austin* Plasmas have found application in metamaterials (MM)as a negative or near-zeropermittivity component. The permittivity of a plasma depends on its electron density, which can be influencedby an applied field. This means that plasmas can be used in MM to actively control the passageof incident waves, leading to applications in switching and power limiting. Numerical modeling of MMis inherently challenging due to disparate spatial and temporal scales. MMcomponents are typically much smaller than the wavelength they're designed to interact with. When a microplasma is generated by the MM, then the scale lengthsbecomeeven more disparate. Furthermore, capturing interesting physics in the plasma sheath region poses an even harder challenge. In all, plasma MM-scale lengths and times can vary over or orders of magnitude. Flux-conservative methods on tree-based grids have shown to be effective in simulating multiscale plasma dynamics in static fields. In this work we address the corresponding techniques for multiscale modeling of plasma dynamics in dynamic fields, and the treatment of those dynamic fields via a multiscale Finite-Difference Time-Domain technique. Usingthese techniques, we can adaptively refine the simulation mesh as the plasma moves in the domain.

*We would like to acknowledge support from an AFOSR MURI with Dr. Mitat Birkan as program manager.

11:00

WF1 4 Ultrasound Generation from Arrays of Microcavity Plasmas JINHONG KIM, SUNG-JIN PARK, GARY EDEN, *University of Illinois, Department of Electrical and Computer Engineering* The generation of ultrasound (20–250 kHz) by arrays of microcavity plasmas has been demonstrated. When the microplasmas are excited by a sinusoidal voltage (20–60 kHz), harmonics as high as m = 12 are detected by a condenser microphone. Each of the ultrasound harmonics matches the harmonics observed in the Fourier representation of the microplasma array current. The intensity of ultrasound can be adjusted by altering the geometry of the microcavity plasmas. Due to the limited bandwidth of the condenser microphone, the highest detectable frequency of in these experiments is 250 kHz at present. As an alternative to microphone detection, a modified Michelson interferometer has been constructed and has successfully detected ultrasound emission from the plasma arrays at frequencies up to 400 kHz.

11:15

WF1 5 Research on Initial Plasma Development in the Laser Triggered Vacuum Switch* YUCHEN LIU, ZHENGHAO HE, *Huazhong University of Science & Technology* In this paper, a multi-electrode laser-triggered vacuum switch (LTVS) is developed to meet the requirements of the pulsed power technology. A pre-breakdown current trigger circuit has been built to investigate the initial process before the switch closes. Under the effects of the pulse laser, the target material generates initial plasma, then the plasma develops and increases because of the effects from electric field. It is found that the initial plasma current increases with the increase of the main gap voltage and the laser energy, and the initial charge amount generated by the laser trigger is approximately the same as the logarithm of the peak power of the laser.

*Supported by National Natural Science Foundation of China Grant No 51377071.

11:30

WF1 6 Next generation high-current switching devices, based on Cs-Ba plasma ALEKSANDR MUSTAFAEV, *Saint Petersburg Mining University, Saint Petersburg, Russia* VICTOR KUZNETSOV, *Ioffe Institute RAS, Saint Petersburg, Russia* VLADIMIR SOUKHOMLINOV, *Saint Petersburg State University, Saint Petersburg, Russia* ARTEM GRABOVSKIY, *Saint Petersburg Mining University, Saint Petersburg, Russia* In this talk we discuss the research into plasma's electro kinetic parameters of Knudsen high-current diode and triode switching devices. It was found that the phenomenon of spontaneous current breakage has a big influence on the efficiency of discharge quenching. Unique regimes for grid discharge quenching were attained: the increase in the modulated power is accompanied by the decrease in the power consumption. Unprecedented energy parameters were obtained: stable frequency modulation in the range from 1 to10 kHz, an anode potential of 50 V, the electric power density of 5 kW/cm^2 and the efficiency more than 95%. Experiments with the grid-less modulator based on the thermionic diode demonstrate the following results: The current modulation is formed as result of plasma structure generation in the electrode gap without applying any external forces. The experiments on the Cs-Ba Knudsen diode demonstrate the feasibility of creating a full current modulation at an ignition voltage of 5...6 V and a discharge current density of ~10 A/cm^2. At a gap of 0.2...2 mm, a stable current and voltage modulation of 5...20 kHz frequency exists in a Cs-pressure range from 1.510^{-3} to 3.510^{-3} Torr. The possibility of the modulation process control via additional external forces was discovered.

11:45

WF1 7 FEM Simulation of Antenna Self-Inductance Effects in ICP MAKOTO MORIYAMA, KEIJI NAKAMURA, *Chubu University* IVAN GANACHEV, *Shibaura Mechatronics Corporation also with Chubu University* Inductively coupled plasma (ICP) has been widely used in the manufacturing of semiconductor devices. It is generated by inductive electric (E) field produced by the RF current of a coil antenna isolated from the plasma by a dielectric window. Large-amplitude RF voltage appears along the coil due to the coil's self-inductance resulting in strong electrostatic E-field near the antenna terminals. This amounts to capacitive coupling and increases the negative (with respect to the plasma bulk) self-bias potential on the window surface Acceleration in this sheath produces more energetic ions, and the ion bombardment often causes unwanted window sputtering. In this study we estimate sheath formation and self-bias voltage using commercially available FEM software. In one example ion bombarding energy of about 100 eV was observed in a 20 mTorr argon ICP driven by 13.56 MHz 40 App RF current in a one-turn coil antenna. The self-induced RF voltage at the antenna terminals was 1200 Vpp. The plasma was cylindrical with radius of 30 cm and height of 15 cm, which are typical conditions and size for plasma sources used in semiconductor device manufacturing. Next we will aim to evaluate antenna and electrostatic-shield designs for reducing the unwanted capacitive coupling

SESSION WF2: PLASMA-SURFACE INTERACTIONS
Friday Morning, 10 November 2017
Room: Duquesne at 10:00
Svetozar Popovic, Old Dominion University, presiding

Contributed Papers

10:00

WF2 1 Influence of Combined Steady-State and Transient Plasma Impact on Tungsten Surface Behavior MAKSYM MYROSHNYK, OLEKSII GIRKA, IVAN BIZYUKOV, ALEXANDER BIZYUKOV, *V.N. Karazin Kharkiv National University* IGOR GARKUSHA, STANISLAV HERASHCHENKO, VADIM MAKHLAJ, *Institute of Plasma Physics NSC "Kharkiv Institute of Physics and Technology"* SERGEY SUROVITSKIY, SERGEY MALYKHIN, *National Technical University "Kharkiv Polytechnical Institute"* XRD ANALYSIS TEAM, QSPA KH-50 TEAM, SCHOOL OF PHYSICS AND TECHNOLOGY TEAM Three Plansee tungsten samples with residual stresses about -350 MPa and texture (100), (100) and (110) have been irradiated with combined steady-state hydrogen ion fluxes (generated by Falcon ion source: 2 keV, 1.7 MWm^{-2}, 10^{22} m^{-2}s^{-1}, 2×10^{26} m^{-2}) and the pulsed plasma loads (generated by QSPA Kh-50: 0.45 MJ/m^2, 0.25 ms) after preliminary SEM and XRD analysis. Steady-state irradiation results in full annealing of initial compression residual stresses. Pulsed QSPA plasma loads lead to creation of symmetrical thermal tensile stresses of +650 MPa in two samples with (100) texture and +125 MPa in third sample with texture (110). Such stress relaxation in third sample caused by cracks and pores formation. Subsequent stationary heat and particle loads lead to relaxation of tensile stresses and increase of number of pores in to 3 times in the target with cracks, which is agreed with increase in number of vacancies complexes in irradiated surface. Presence of steady-state ion and heat flux allows to avoid/predict cracking threshold for texturized tungsten.

10:15

WF2 2 In Situ Measurement of Electron Emission Yields from Plasma-Exposed Surfaces MARK SOBOLEWSKI, *National Institute of Standards and Technology* Accurate plasma simulations require knowledge of the flux or yield of electrons emitted from plasma-exposed surfaces. Yields can be measured in beam studies, but it is usually impractical to produce a beam of each possible energetic particle that could be produced by the plasma. In contrast, in-situ measurements, performed during plasma exposure, may provide useful values or bounds for effective or total electron emission yields, summed over all or some subset of the energetic particles present in a given plasma. Here, measurements were performed in an inductively coupled plasma system equipped with variable-frequency rf bias. An insulating cap is placed on the rf-biased electrode to minimize edge effects. The rf voltage and current across the sheath adjacent to the rf-biased electrode are measured and analyzed by detailed, numerical sheath models, which allow the current of emitted electrons to be distinguished from other mechanisms of current flow. The observed dependence on voltage and rf phase allows some discrimination between emission induced by energetic positive ions and that induced by photons and metastables. The technique is validated by comparing results from argon discharges with beam studies and then is applied to plasma etching discharges in fluorocarbon gases.

10:30

WF2 3 Surface Erosion of MAX Phase Micro-Trenches using a Plasma Jet from an Electrothermal Plasma Source* JONATHAN COBURN, *North Carolina State University* T. E. GEBHART, CHAD PARISH, EZEKIEL UNTERBERG, DONALD HILLIS, *Oak Ridge National Laboratory* MOHAMED BOURHAM, *North Carolina State University* Erosion characteristics of plasma-facing component (PFC) materials must be evaluated under extreme edge localized mode (ELM) and hard disruption conditions. Investigation of material alternatives to tungsten is essential, allowing for solutions suitable for operating magnetic fusion reactor environments. Novel MAX phase ceramics were exposed to an electrothermal (ET) plasma source operated at Oak Ridge National Laboratory. A technique was developed using a dual FIB/SEM to carve micrometer-scale trenches into the surface of polished MAX samples. FIB ruler markings were etched in $\sim 1\mu m$ increments on a trench wall shadowed from plasma exposure. These samples were exposed to a lexan ET plasma stream in a He environment, at a specified impact angle, with IR camera and visible spectrometer diagnostics. Current pulses of 8 kA over 160 μs yielded heat fluxes of a few GW/m^2 on the sample surface. Post-experiment SEM analysis indicated that this heat flux was enough for surface melting and boiling, but not enough to achieve a fully sublimating erosion regime. FIB ruler markings indicate $\sim 1\mu m$ of erosion depth in melted/vaporized areas. Results encourage higher heat flux ET exposures for future studies of MAX phases, SiC, and other novel materials using this micro-trenching technique.

*Work was supported by UT Battelle, LLC Subcontract 4000145506.

10:45

WF2 4 Plasma-Surface Interactions at Atmospheric Pressure: Polystyrene Etching and Surface Modification by a Plasma Jet* PINGSHAN LUAN, *Univ of Maryland-College Park* V. S. SANTOSH K. KONDETI, *Univ of Minnesota-Twin Cities* ANDREW KNOLL, *Univ of Maryland-College Park* PETER BRUGGEMAN, *Univ of Minnesota-Twin Cities* GOTTLIEB OEHRLEIN, *Univ of Maryland-College Park* In this work we studied the interaction of a well-characterized radio frequency (RF) atmospheric pressure plasma jet (APPJ) with polystyrene (PS) as a model polymer. A number of plasma processing parameters, such as treatment distance and angle, feed and environment gas compositions, were investigated by evaluating both polymer thickness and surface chemical composition change after treatment. The effect of different plasma species on polymer surface was compared. We found that for both Ar/O_2 and Ar/H_2O plasma the etch rate of PS decayed exponentially with treatment distance, whereas surface oxidation increased to a maximum and then decreased. Both the exponential decay constant and oxidation maximum varied with gas composition due to changes in the gas phase species. A surface reaction model based on Langmuir adsorption can explain the observed difference in trends. The reaction rate between incident atomic O or OH radical flux and etched C flux was estimated. Besides, the apparent activation energy (E_a) of etching reactions was measured by varying substrate temperature.

*We gratefully acknowledge funding from National Science Foundation (PHY-1415353) and US Department of Energy (DE-SC0001939).

11:00

WF2 5 Surface ripple formation during plasma etching of silicon KOUICHI ONO, NOBUYA NAKAZAKI, HIROTAKA TSUDA, YOSHINORI TAKAO, KOJI ERIGUCHI, *Kyoto University* Atomic- or nanometer-scale roughness on feature surfaces has become an important issue to be resolved in the fabrication of nanoscale devices. Control of the surface roughening during plasma etching might be possible, given a deeper understanding of plasma-surface interactions concerned with it. We have investigated the surface morphology evolution in response to ion incidence angle onto substrate surfaces during silicon etching in chlorine-based plasmas, through Monte Carlo simulations and experiments using sheath control plates. The simulations showed randomly roughened surfaces at normal incidence, while ripple structures at off-normal angles of incidence, traveling laterally across the surface in the direction of ion incidence. Correspondingly, the experiments demonstrated sawtooth-like ripples whose crests/troughs are elongated perpendicularly to the direction of ion incidence at intermediate off-normal angles, while small ripples or slit-like grooves whose crests/toughs are parallel to the direction of ion incidence at high off-normal angles, as predicted by simulations. These results are discussed in terms of the effects of ion reflection from feature surfaces and those of geometrical shadowing of the feature.

11:15

WF2 6 Comparison of Polymer Etching Mechanisms by Cold Atmospheric Plasma (CAP) Sources Under Well-Defined Conditions* ANDREW KNOLL, PINGSHAN LUAN, ADAM PRANDA, GOTTLIEB OEHRLEIN,[†] *University of Maryland College Park* Cold atmospheric plasma sources are important sources of reactive chemical species that can used to deactivate bacteria and biomolecules or modify surfaces under mild conditions, leading to use in numerous applications. We examine varying substrate temperature on polymer etching using an atmospheric pressure plasma jet (APPJ) and a surface microdischarge (SMD) source. The APPJ shows high etch rates but mild surface modification whereas the SMD shows no etching at room temperature but significant surface modification. An Arrhenius equation is used to fit the temperature dependence of etch rate and yields apparent activation energies. APPJ treatment activation energy increases as a function of distance from 0.2 eV up to 0.5 eV. The activation energy of the SMD source is significantly higher than the APPJ at 0.8-0.9 eV and overall causes less etching. The directionality of etching is investigated using patterned samples. APPJ etching has anisotropy which becomes more isotropic with increasing treatment distance where the

SMD has only isotropic etching. APPJ induced etching of these polymers must include other reactive species than neutral species alone, potentially line-of-sight charged particles, that enhance the rate of chemical etching. SMD etching is consistent with neutral chemical etching only, highlighting key differences between these two sources.

*The authors gratefully acknowledge financial support by US Department of Energy (DE-SC0001939) and National Science Foundation (PHY-1415353).
†Corresponding author.

11:30
WF2 7 Deuterium uptake by Sn films on a W substrate OLUSEYI FASORANTI, BRUCE KOEL, *Princeton University* Sn is under consideration as a liquid-metal plasma-facing component for high power load applications in the divertor region of fusion reactors due to potential abilities for self-recovery and heat-flux management. Improved fundamental understanding of deuterium-Sn interactions that occur in Sn films on W substrates will be useful for further evaluating the compatibility of this system with fusion reactors. We report on surface science experiments under UHV conditions exploring the thermal stability and deuterium uptake by Sn films on polycrystalline W substrates using surface diagnostic tools such as AES, XPS, LEIS, and TPD. Our results show that multilayer Sn films start to evaporate near 1170 K, but the Sn monolayer on W is not fully removed until 1800 K. Clustering or diffusion of Sn films was observed above 310 K. Deuterium uptake on Sn films at 310-750 K from irradiation using 700 eV D^{2+} ions showed lower uptake on liquid Sn films compared to solid Sn. Oxidation of solid and liquid Sn films by O2 was studied using XPS, with more extensive oxidation at higher temperature. TPD shows Sn loss from SnO2 films at below the Sn multilayer desorption temperature. Irradiation of these oxidized Sn films by 700 eV D^{2+} caused reduction of the film to metallic Sn.

SESSION WF3: ENVIRONMENTAL AND ENERGY APPLICATIONS
Friday Morning, 10 November 2017
Room: Oakmont Junior Ballroom at 10:00
Jiang Chunqi, Old Dominion University, presiding

Contributed Papers

10:00
WF3 1 Upgrading Biomass into Higher Value Chemicals by Using Low Temperature Plasma ELIJAH THIMSEN, YU GAO, NECIP UNER, JAMES MEYER, MARCUS FOSTON, *Washington Univ* Low temperature plasmas (LTP) have been successively progressing into a general tool for solids processing. In this study, we focus on the interaction of a radio frequency low temperature plasma with a morphologically and chemically complex substrate: lignocellulosic biomass (i.e. switchgrass). As an alternative to conventional thermal decomposition for converting biomass into higher value products, we propose a new type of reactor based on LTP. LTP is intriguing for the conversion of biomass into higher value products because the nonequilibrium environment may provide selectivity that is unfavorable in thermal processes. Preliminary experiments on switchgrass in an argon/hydrogen plasma show promising reaction rates and a relatively narrow product spectrum. The solid feedstock is directly converted into simple hydrocarbons that are deoxygenated (e.g. $C_{2-4}H_x$) with high mass yield of approximately 8%. The plasma process does not require precious metal catalysts to perform the conversion, a feat that is nearly impossible in a single step by conventional thermal methods. A study of the effects of gas composition, power density, pressure and biomass feedstock on final product distribution will be presented.

10:15
WF3 2 Effective species in ignition processes of premixed burner flame with superposition of dielectric barrier discharge K. SASAKI, Y. DEGUCHI, *Hokkaido University* We have identified the most effective species in the plasma-assisted ignition of a premixed burner flame by comparing the propagation speed of the flame kernel with the densities of radicals. The candidate radicals were OH and atomic oxygen. The spatial distributions of densities of OH and atomic oxygen were measured by (two-photon absorption) laser-induced fluorescence spectroscopy. The propagation speed of the flame kernel was measured by shadowgraph imaging. It was observed that the flame kernel in the bottom part, which was located at a closer distance from the exit of the afterglow gas from a dielectric barrier discharge, had a higher propagation speed than the top part. The spatial distribution of the OH density was gentle, and we did not find significant difference in the OH density at the bottom and top parts of the flame kernel. On the other hand, the density of atomic oxygen had a steeper distribution, and the density at the top part of the flame kernel was much lower than that at the bottom. On the basis of these experimental results, we have concluded that atomic oxygen is more effective than OH radical in the ignition of the premixed burner flame.

10:30
WF3 3 Combined experimental and modeling study of direct plasma conversion of methane* JOSEPH TOTH, XIAOZHOU SHEN, DANIEL LACKS, R. MOHAN SANKARAN, *Case western Reserve University* The direct conversion of methane without oxidizing chemistry is desired to avoid COx species and produce hydrogen or higher order hydrocarbons. However, the methane molecule is difficult to dissociate by thermal energy alone and tends to coke and inactivate catalysts. Here, we studied atmospheric-pressure, non-equilibrium plasmas for the direct conversion of methane. A key contribution of our work is that the discharge was spatially confined to decouple power and volume effects on methane conversion. In support of experimental results, a microkinetic model was developed, solving 352 elementary reactions involving 36 species including neutrals, ions, and radicals that takes into consideration both spatial and temporal dependencies of the filamentary behavior. Our results show that while methane conversion increases with increasing plasma power, it is relatively independent of volume. Since volume is controlled, these trends reflect the importance of power density. The product distributions are a stronger function of power at small volumes, with a tendency to form hydrocarbons at lower volumes and powers, and hydrogen and solid carbon at higher volumes and powers.

*We acknowledge the Donors of the American Chemical Society Petroleum Research Fund for support of this research.

10:45
WF3 4 Plasma Conversion to Electrify Chemical Industry GERARD VAN ROOIJ, DIRK V.D. BEKEROM, NICOLA GATTI, TEOFIL MINEA, SRINATH PONDURI, QIN ONG, WALDO BONGERS, RICHARD V.D. SANDEN, *DIFFER* A promising option to mitigate intermittency and to achieve sector integration is plasma synthesis of chemicals and artificial fuels using sustainable energy. This is illustrated on basis of a common microwave reactor approach that is evaluated experimentally with laser Rayleigh and Raman scattering and Fourier transform infrared spectroscopy. For

example, 50% energy efficiency was observed in pure CO_2 (forming CO and O_2) in a thermodynamic equilibrium conversion regime governed by gas temperatures of $\sim$3500 K. These results are interpreted on basis of Boltzmann solver based plasma dynamics estimates, indicating that intrinsic electron energies are higher than what is favorable for preferential vibrational excitation. Pulsed experiments (1-5 kHz) in which gas temperature dynamics are revealed confirm this picture. In pure N_2, vibrational temperatures are observed in excess of 10000 K and up to five times higher than the gas temperature. Overpopulation of higher levels is confirmed. These observations are promising in view of economic localized production of fertilizer. An outlook is given to novel reactor approaches that tailor the plasma dynamics to optimally promote vibrational excitation and to achieve the desired non-equilibrium.

Invited Papers

11:00
WF3 5 Peroxynitric acid ($HOONO_2$) is the key chemical species of plasma-treated water for effective and safety disinfection*
KATSUHISA KITANO, *Osaka University*

For the plasma disinfection of human body, sterilization in liquid is crucial. We found that the plasma-treated water (PTW) has strong bactericidal activity under low pH. Physicochemical properties of PTW is discussed based on chemical kinetics. Lower temperature brings longer half-life, and the bactericidal activity can be kept by cryopreservation. High performance PTW, corresponding to the disinfection power of 22 log reduction (*B. subtilis* spore), can be obtained by special plasma system with cooling. This is equivalent to 65% H_2O_2 and 14% NaClO, which are deadly poison. But, it is deactivated soon at higher temperature (4 sec. at body temp.), and toxicity seems low. Many researchers are interested in this area of PTW, where the waters are treated by their original devices. For scientific approach, we should discuss based on chemical species. Although PTW contains many chemical components, respective chemical components were separated by ion chromatography (IC). To examine the bactericidal activities of respective components, bactericidal assays were done with respective fractions of eluate. In addition to peaks of H_2O_2, NO_2^- and NO_3^-, a specific peak was detected and only this fraction had bactericidal activity. This means that active ingredient was successfully purified. Moreover, molecular nitrogen was required both in the ambient gas and in the distilled water used to prepare the PTW. We, therefore, propose that the reactive molecule in PTW with bactericidal effects is not a free reactive oxygen species but nitrogen atom-containing molecules that release O_2^-, such as HOONO (peroxynitrous acid) or $HOONO_2$ (PNA: peroxynitric acid). Considering the activation energy for degradation, we assumed that PNA is active ingredient. From IC analysis of chemical synthesized PNA, a same specific peak was seen. So we conclude that PNA is a key chemical species of cryo-preserved PTW with the reduced-pH method, while there is no report about sterilization by PNA.

*JSPS KAKENHI Grant Number 15H03583.

Contributed Papers

11:30
WF3 6 Modelling nitrogen fixation by electron-beam sustained discharges MILES M. TURNER, *Dublin City University* Nitrogen fixation is a plasma application recently attracting renewed interest. Nitrogen is an essential biochemical. However, atmospheric nitrogen is almost inert, so that nitrogen is scarce in the biosphere, and access to nitrogen is a major limiting factor on plant growth, and hence agricultural productivity. Converting atmospheric nitrogen into biologically useful forms such as nitrates is known as nitrogen fixation. Artificial nitrogen fixation is now achieved by a fossil fuel powered process (Haber-Bosch). Continued use of this method is likely unacceptable on environmental grounds, and alternatives are consequently being sought. A plasma process driven by electricity from renewable resources is an alternative. Major challenges in this context include reaching acceptable efficiency, and operating on a sufficiently large scale. Electron-beam sustained discharges are a promising avenue, since they offer to produce large volume plasmas at atmospheric pressure under closely controlled conditions. This paper will discuss a modelling study investigating the operation of such discharge for nitrogen fixation. We will show that energy efficiency close to Haber-Bosch appears possible (with appreciable uncertainty, however).

NOTES

NOTES

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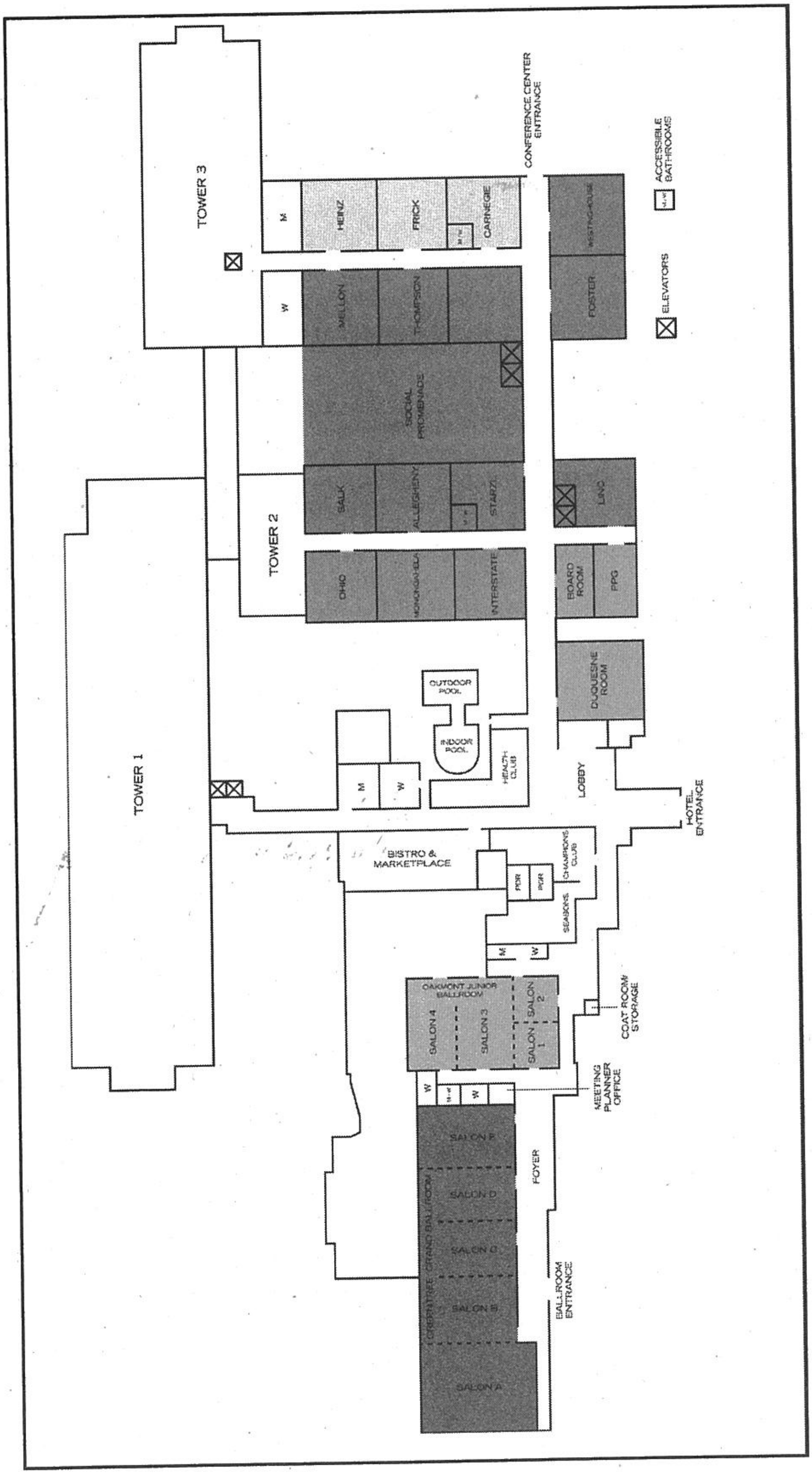

Epitome of the 70th Annual Gaseous Electronics Conference

09:00 MONDAY MORNING
06 NOVEMBER 2017

AM1 **Linking Academia & Industry**
Room: Salon D

AM4 **Scientific Paper Writing Workshop**
Room: Foster

14:00 MONDAY AFTERNOON
06 NOVEMBER 2017

BM1 **Practical Challenges for Industry**
Room: Salon D

BM2 **Linking Theory & Experiment**
Room: Dusquene

18:00 MONDAY EVENING
06 NOVEMBER 2017

CM1 **Welcome Reception**
Room: Oakmont Junior Ballroom

08:00 TUESDAY MORNING
07 NOVEMBER 2017

DT1 **Microdischarges I**
Remi Dussart
Room: Salon D

DT2 **Diagnostics I**
Room: Duquesne

DT3 **Bio-Medical Plasma Chemistry**
Satoshi Uchida
Room: Oakmont Junior Ballroom

10:00 TUESDAY MORNING
07 NOVEMBER 2017

ET1 **Plasmas in Liquids I**
Paul Maguire
Room: Salon D

ET2 **Modeling and Simulation I**
Victor Pasko
Room: Duquesne

ET3 **Plasma Etching for Semiconductor Processing**
Keizo Kinoshita, Mingmei Wang
Room: Oakmont Junior Ballroom

13:30 TUESDAY AFTERNOON
07 NOVEMBER 2017

FT1 **Inductively Coupled Plasmas**
Room: Salon D

FT2 **Plasma Boundaries and Sheaths**
Michael Campanell
Room: Duquesne

FT3 **Heavy Particle Collisions**
Xinwen Ma, Ladislau Nagy
Room: Oakmont Junior Ballroom

16:00 TUESDAY AFTERNOON
07 NOVEMBER 2017

GT1 **Poster Session I**
Room: Salon ABC

08:00 WEDNESDAY MORNING
08 NOVEMBER 2017

JW1 **Gas Phase Plasma Chemistry I**
Room: Salon D

JW2 **Diagnostics II**
Jim Franek
Room: Duquesne

JW3 **Antimatter and Other Processes**
Michael Charlton, Stephen Buckman
Room: Oakmont Junior Ballroom

10:00 WEDNESDAY MORNING
08 NOVEMBER 2017

KW1 **The Will Allis Prize for the Study of Ionized Gases**
Klaus Bartschat
Room: Salon D

11:00 WEDNESDAY MORNING
08 NOVEMBER 2017

LW1 **Business Meeting**
Room: Salon D

13:30 WEDNESDAY AFTERNOON
08 NOVEMBER 2017

MW1 **Microdischarges II**
David Go
Room: Salon D

MW2 **Non-equilibrium Kinetics of Low-temperature Plasmas**
Svetlana Starikovskaia
Room: Duquesne

MW3 **Modelling of Propulsion and E×B Plasmas**
Francesco Taccogna
Room: Oakmont Junior Ballroom

16:00 WEDNESDAY AFTERNOON
08 NOVEMBER 2017

NW1 **Poster Session II**
Room: Salon ABC

19:00 WEDNESDAY EVENING
08 NOVEMBER 2017

PW2 **LXCat Discussion**
Room: Duquesne

08:00 THURSDAY MORNING
09 NOVEMBER 2017

QR1 **Magnetically Enhanced Plasmas I**
Room: Salon D

QR2 **Diagnostics III**
Igor Adamovich
Room: Duquesne

QR3 **Collisions with Atoms**
N.L.S. Martin, Marcelo Ambrosio
Room: Oakmont Junior Ballroom

10:00 THURSDAY MORNING
09 NOVEMBER 2017

RR1 **Plasmas at Special Conditions**
Room: Salon D

RR2 **High Pressure Discharges**
Room: Duquesne

RR3 **Electron-Molecule Collisions**
Dmitry Fursa, Xiangjun Chen
Room: Oakmont Junior Ballroom

13:30 THURSDAY AFTERNOON
09 NOVEMBER 2017

SR1 **Modeling and Simulation II**
Hae June Lee, Jannis Teunissen
Room: Salon D

SR2 **Plasmas in Liquids II**
John Foster
Room: Duquesne

SR3 **Capacitively Coupled Plasmas**
A.R. Gibson
Room: Oakmont Junior Ballroom

16:00 THURSDAY AFTERNOON
09 NOVEMBER 2017

TR1 **Magnetically Enhanced Plasma II**
Denis Eremin
Room: Salon D

TR2 **Dissociation, Recombination, and Attachment**
Ioan F. Schneider, Nicholas Shuman
Room: Duquesne

TR3 **Biomedical Plasmas**
Klaus-Dieter Weltmann, Eric Robert
Room: Oakmont Junior Ballroom

18:30 THURSDAY EVENING
09 NOVEMBER 2017

UR1 **Reception and Banquet**
Room: Salon ABC

08:00 FRIDAY MORNING
10 NOVEMBER 2017

VF1 **Nanoparticles**
Room: Salon D

VF2 **Gas Phase Plasma Chemistry II**
Room: Duquesne

VF3 **Surface Treatment and Deposition**
Room: Oakmont Junior Ballroom

10:00 FRIDAY MORNING
10 NOVEMBER 2017

WF1 **Reconfigurable and Interacting Plasmas**
Sergey Macheret
Room: Salon D

WF2 **Plasma-Surface Interactions**
Room: Duquesne

WF3 **Environmental and Energy Applications**
Katsuhisa Kitano
Room: Oakmont Junior Ballroom

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