66th Annual
Gaseous Electronics Conference

September–October, 2013

Princeton, New Jersey
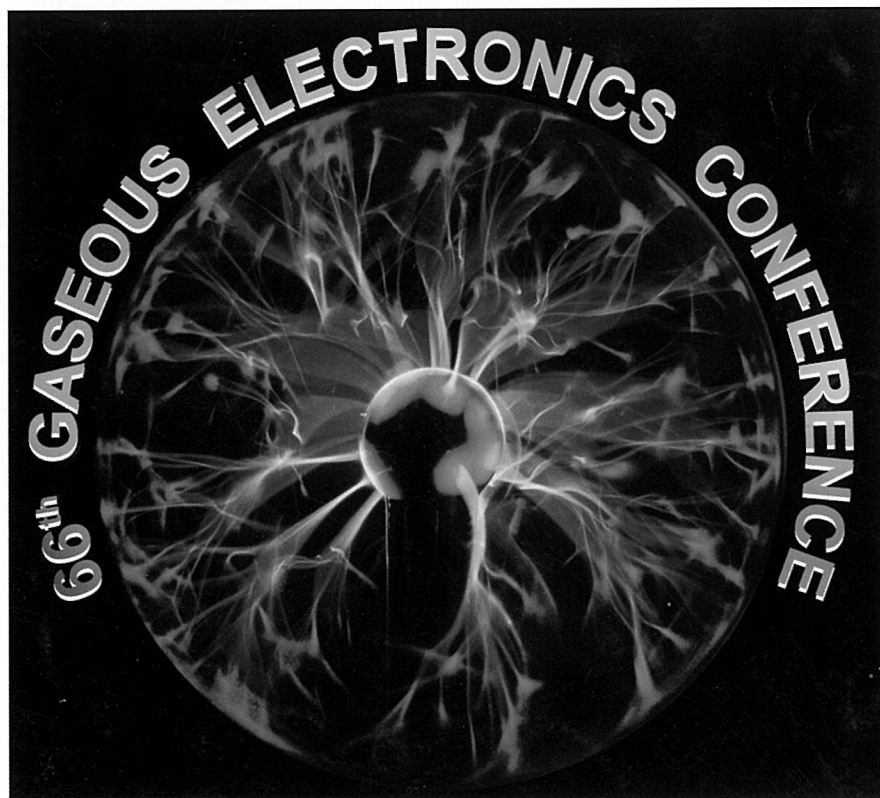
APS physics™

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66th Annual
Gaseous Electronics Conference

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GENERAL INFORMATION

Welcome to Princeton, New Jersey. America's best minds have been visiting and meeting in Princeton, for more than 200 years, from the first sessions of the Continental Congress to today's scientific and corporate conventions. Princeton University, located in the heart of Princeton, welcomes visitors to its historic campus. The Princeton region is filled with abundant amenities, including world-class hotels, restaurants, museums, historic sites, theaters, and sports arenas. All of this in a region that evolved from significant events of American history and is known for its charming old fashioned shopping villages, monuments, and beautiful parks. An excellent transportation network of bus, rail and highways puts Princeton within easy reach of major urban centers: Philadelphia and Trenton to the south, Newark and New York to the north. International airports are located in Philadelphia, Newark and New York. Bus and train stations to these cities are adjacent to campus.

The 66th Gaseous Electronics Conference (GEC) of the American Physical Society is being held at the Westin Princeton Hotel at Forrestal Village. The hotel is nestled in the picturesque Forrestal Village, and is adjacent to Princeton University's Forrestal Campus.

The conference will bring together approximately 400 plasma scientists and engineers from United States and other countries who will attend 32 invited talks, 241 oral contributed talks, and 216 poster presentations. The GEC technical program includes the GEC Foundation Talk, preconference tutorials on Saturday and Sunday, two daylong preconference workshops on Monday, an opening reception on Monday evening, two workshops and tour of PPPL on Tuesday, a Thursday evening awards banquet, and a Friday afternoon special session devoted to the Scientific Legacy of Arthur Phelps.

The GEC will also present the "Student Award for Excellence" to the best student oral presentation, selected from a group of four finalists.

SPECIAL SESSIONS AND EVENTS

The GEC Executive Committee is pleased to announce that the GEC Foundation Talk will be presented by Rod Boswell from The Australian National University. His talk entitled *Thinking and Doing, a Long Way to the Top in Commercialization* will be given at 10:30 am on Wednesday, October 2 in Ballroom.

A preconference tutorial *Fundamental Processes, Modeling and Diagnostics of Low-Temperature Plasmas* will be given on Saturday and Sunday, September 28-29. Course Facilitators are Igor D. Kaganovich (PPPL) and Jose L. Lopez (Seton Hall University). The preconference tutorial is offered as an educational service from the DOE Center for *Predictive Control of Plasma Kinetics: Multi-phase and Bounded Systems*. The objective of this short course is to provide background and outline recent developments in plasma processing applications. It will cover basics of RF discharges (M.A. Lieberman, R. Boswell), plasma surface interaction (V.M. Donnelly, R. Boswell), probe diagnostics (V.A. Godyak, V.I. Demidov, and Y. Raitses) and numerical modeling with Vlasov codes (V.I. Kolobov) and PIC codes (D. Sydorenko), as well as kinetic theory (I.D. Kaganovich).

Two daylong workshops workshop will be held on Monday, September 30.

SESSION AM1

Plasma-Surface Interactions: From Fusion to Semiconductor Processing
Monday, September 30 • 8 am
Organizers: Yevgeny Raitses (Princeton Plasma Physics Laboratory), Vincent M. Donnelly (University of Houston), David B. Graves (University of California -Berkeley), Greg de Temmerman (Dutch Institute for Fundamental Energy Research)

SESSION AM2

Weakly-ionized non-equilibrium air plasma at moderate and high pressures: generation and maintenance, modeling, diagnostics and applications
Monday, September 30 • 8:30 am
Organizers: Mikhail Shneider, Richard Miles (Princeton University), and Greg Fridman (Drexel University)

Two additional workshops will be held on Tuesday, October 1:

SESSION DT4

Mysteries and Challenges of Negative Ion Sources
Tuesday, October 1 • 10 am
Organizers: Robert F. Welton (Oak Ridge National Laboratory), Rod Boswell (The Australian National University), Larry Grisham (Princeton Plasma Physics Laboratory)

SESSION ET5

3rd GEC Workshop on the Plasma Data Exchange Project
Tuesday, October 1 • 1:30pm
Organizers: Leanne Pitchford (Laplace CNRS and University of Toulouse), William G. Graham (Queen's University Belfast)

A tour of the Princeton Plasma Physics Laboratory is planned for the evening of Tues. Oct. 1st starting at 6:00 pm. A bus will take participants to PPPL where tour guides will introduce experimental facilities.

An additional Friday afternoon special session will be held on Friday, October 4.

SESSION UF1

Scientific Legacy of Arthur Phelps (1923-2012)
Friday, October 4 • 1:30pm
Organizers: Biswa N. Ganguly (Air Force Research Laboratory, Wright-Patterson), James E. Lawler (University of Wisconsin-Madison), Leanne Pitchford (Laplace CNRS and University of Toulouse)

GEC SESSIONS

Session Numbering Scheme: Each session has a code consisting of a letter and a number. The first letter indicates the numbering for that session in the program, e.g., A for 1, B for 2, etc.. The second letter indicates the day of the week, for example, M for Monday, T for Tuesday, W for Wednesday, R for Thursday, and F for Friday. The last number indicates the room location: 1 for Ballroom I, 2 for Ballroom II, 3 for Nassau room, 4 for Fountain View room, and 5 for Village Square room.

AM1 ....Workshop on Plasma Surface Interaction: From Fusion to Semiconductor Processing

AM2 ....Workshop on Weakly-ionized non-equilibrium air plasma at moderate and high pressures: generation and maintenance, modeling, diagnostics and applications

BM1 ....Welcome Reception

CT1 ....Poster Session I

DT1 ....Basic Phenomena in Low Temperature Plasma Physics

DT2 ....High Pressure Discharges: Dielectric Barrier Discharges, Coronas, Breakdown, Sparks I

DT3 ....Liquids I

DT4 ....Workshop on the Mysteries and Challenges of Negative Ion Sources

ET1................Glows: dc, pulsed, microwave, others

ET2................Microdischarges I

ET3................Green Plasma Technologies I

ET5................Workshop on the Plasma Data Exchange Project

FT1 ....Non-equilibrium Kinetics of Low-temperature Plasmas

FT2................High Pressure Discharges: Dielectric Barrier Discharges, Coronas, Breakdown, Sparks II

CONFERENCE FORMAT

The GEC will host most of its sessions on the 1st level of the Westin Hotel in Princeton, NJ. Refreshments will be provided daily outside of the ballroom at 9:30 and 3:00 pm, except for Friday when the morning break will be at 10am. There will be two parallel sessions on Monday, five on Tuesday, and four parallel sessions throughout the rest of the week. There will be three poster sessions that will be held in the ballroom foyer on Tuesday, Wednesday and Thursday mornings from 8:00 am to 9:30 am. Posters may remain on display until the end of each day.

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. Oral contributed talks are allotted 12 minutes, with 3 additional minutes for questions and discussion. Poster boards measure 4 feet by 8 feet. The posters can remain on display throughout the day and should be removed at the close of each day.

GEC STUDENT AWARD FOR EXCELLENCE

The GEC Executive Committee will award a $1000 prize for best oral presentation by a student. Their advisor must have nominated a student before being selected by GEC Executive Committee members to present and compete for the Excellence Award. Student award finalists will present his or her work on Wednesday, October 2 and Thursday October 3. Students competing for the award, in the order of their appearance in the GEC 2013 program are:

Sachin Sharma, Missouri University of Science & Technology, USA,
"Interference in Recoil-Ion Momentum Spectra for Ionization in p+ H2 collisions"
Oct. 2, 4:00 pm, Village Square
SESSION LW5

Michael Campanell, Princeton Plasma Physics Laboratory, USA
"Instability and Inversion of the Sheath Potential Caused by Electron Emission"
Oct. 3, 10:45 am, Nassau Room
SESSION NR3

Francois Pechereau, Ecole Centrale Paris, France
"Simulation of the reignition of atmospheric pressure air discharges behind dielectric obstacles: comparison with experiments"
Oct. 3, 2:45 pm, Ballroom I
SESSION PR1

Arthur Greb, York Plasma Institute, Department of Physics, University of York, York
"The role of surface properties in the dynamics of radio-frequency plasma sheaths: measurements and simulations"
Oct. 3, 4:15 pm, Ballroom II
SESSION QR2

At the 2012 GEC in Austin, TX, the GEC Student Award for Excellence was presented to Jerome Bredin, Laboratoire de Physique des Plasmas (LPP), Ecole Polytechnique/CNRS, France, for the oral presentation *"Measurements of Positive and Negative Energy Distribution Function Obtained from a Langmuir Probe in an Ion-Ion Plasma."*

REGISTRATION

The registration desk will be open on Sunday, September 29 from 4:00 to 7:00 pm in the foyer outside the ballroom. Monday through Thursday the registration desk will be open from 7:30 am to 4:00 pm in the same location. The on-site registration fees are:

Regular Attendee $575
Retired/Unemployed..........................$350
Student...$350
One-Day Attendee $350
Guest Banquet Ticket..........................$75

OPENING RECEPTION AND BANQUET

An opening reception will be held from 7:00pm to 9:00pm on Monday, September 30th in the ballroom foyer. On Thursday evening, October 3rd the banquet reception will be held at 6:00 pm in the ballroom foyer followed by the banquet from 7pm to 9pm featuring live musical entertainment and a guest speaker. The cost of the banquet is included in the registration fee. Companion banquet tickets may be purchased for $75.00 at the registration desk on-site through the end of the day on Tuesday, October 3rd. All conference attendees and guests are encouraged to attend. The GEC Award for Student Excellence will be presented during the banquet.

WI-FI AND OTHER BUSINESS SERVICES

Wi-Fi access is complimentary in the sleeping rooms. For a fee, services such as faxing, printing and photocopying are available in the Business Center located on the 1st floor.

AUDIO-VISUAL EQUIPMENT

The technical sessions will be equipped with an LCD projector and amplified sound. Laptops will be provided for the technical sessions.

DINING OPTIONS

The Westin hotel has full service dining and they will provide special hot and cold lunch options for purchase in the hotel lobby. There is a food court outside the hotel.

Food Court Hours
Monday – Saturday: 10:00 am - 9:00 pm
Sunday: 11 am – 6 pm

Princeton Forrestal Village, the location of the Westin hotel, features restaurants, shopping and a fitness center, all within walking distance from the Conference location.

CALL FOR NOMINATIONS FOR GEC GENERAL AND EXECUTIVE COMMITTEES

The GEC Executive Committee welcomes nominations, including self-nominations, for both the General Committee and the Executive Committee. Becoming a General Committee and/or Executive Committee member provides a unique opportunity to see both how the GEC is governed and how one may influence GEC's future direction by helping to define scientific programs and select future venues. This includes selection of special event topics, invited speakers, abstract sorting categories, arranging the technical program, selection of meeting sites, and budgetary decisions.

Please submit your nominations to the GEC Chair or any member of the Executive Committee. At the GEC Business Meeting nominations will be accepted to select five new members of the GEC General Committee. The General Committee meets once a year during the GEC. The Executive Committee meets twice a year, once during the GEC and once during the summer at the Sorters Meeting.

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, then Secretary, and finally as Past Secretary.

The 2013 Business Meeting will take place on Wednesday, October 3rd at 11:30 am in the ballroom at the Westin Hotel.

GEC 2013 EXECUTIVE COMMITTEE

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Japan

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Yevgeny Raitses, Workshops
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yraitses@pppl.gov

GEC 2013 SPONSORS AND EXHIBITORS

Sponsors and Exhibitors allow the GEC Executive Committee to provide many benefits to attendees including travel assistance and an excellence award for junior attendees. The 66th 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.

US Government Agency and Laboratory Sponsors
NSF/DOE Partnership in Basic Plasma Science and Engineering
NSF program "Theoretical Atomic, Molecular, and Optical Physics"
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Due to generous support of sponsors, more than 40 students have received partial travel assistance to attend the conference.

PLEASE NOTE

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Epitome of the 66th Annual Gaseous Electronics Conference

**08:00 MONDAY MORNING
30 SEPTEMBER 2013**

AM1   **Workshop on Plasma Surface Interaction: From Fusion to Semiconductor Processing**
Room: Ballroom I

AM2   **Workshop on Weakly-ionized Non-equilibrium Air Plasma at Moderate and High Pressures: Generation and Maintenance, Modeling, Diagnostics and Applications**
Room: Ballroom II

**18:00 MONDAY EVENING
30 SEPTEMBER 2013**

BM1   **Welcome Reception**
Room: Ballroom Foyer

**08:00 TUESDAY MORNING
01 OCTOBER 2013**

CT1   **Poster Session I (8:00-9:30AM)**
Room: Ballroom Foyer

**10:00 TUESDAY MORNING
01 OCTOBER 2013**

DT1   **Basic Phenomena in Low Temperature Plasma Physics**
Adric Jones
Room: Ballroom I

DT2   **High Pressure Discharges: Dielectric Barrier Discharges, Coronas, Breakdown, Sparks I**
Room: Ballroom II

DT3   **Liquids I**
David Staack, Yakov Krasik
Room: Nassau Room

DT4   **Workshop on the Mysteries and Challenges of Negative Ion Sources**
Room: Fountain View

**13:30 TUESDAY AFTERNOON
01 OCTOBER 2013**

ET1   **Glows: DC, Pulsed, Microwave, Others**
Room: Ballroom I

ET2   **Microdischarges I**
Room: Ballroom II

ET3   **Green Plasma Technologies I**
Tomohiro Nozaki
Room: Nassau Room

ET5   **Workshop on the Plasma Data Exchange Project**
Room: Village Square

**15:30 TUESDAY AFTERNOON
01 OCTOBER 2013**

FT1   **Non-equilibrium Kinetics of Low-temperature Plasmas**
Room: Ballroom I

FT2   **High Pressure Discharges: Dielectric Barrier Discharges, Coronas, Breakdown, Sparks II**
Room: Ballroom II

FT3   **Liquids II**
Fumiyoshi Tochikubo
Room: Nassau Room

**18:00 TUESDAY EVENING
01 OCTOBER 2013**

GT1   **Tour of the Princeton Plasma Physics Laboratory**

08:00 WEDNESDAY MORNING
02 OCTOBER 2013

HW1   **Poster Session II (8:00-9:30AM)**
              Room: Ballroom Foyer

10:00 WEDNESDAY MORNING
02 OCTOBER 2013

IW1   **PPPL Director Welcome and**
              GEC Foundation Talk
              Stewart Prager, Rod Boswell
              Room: Ballroom I & II

11:30 WEDNESDAY MORNING
02 OCTOBER 2013

JW1   **GEC Business Meeting**
              Room: Ballroom I & II

13:30 WEDNESDAY AFTERNOON
02 OCTOBER 2013

KW1   **Inductively Coupled Plasmas**
              Room: Ballroom I

KW2   **Microdischarges II**
              Natalia Babaeva
              Room: Ballroom II

KW3   **Green Plasma Technologies II**
              Richard van de Sanden
              Room: Nassau Room

KW5   **Electron and Positron Collisions**
              with Atoms
              S.J. Ward, Dario Mitnik
              Room: Village Square

15:30 WEDNESDAY AFTERNOON
02 OCTOBER 2013

LW1   **Plasma Etching**
              Kaushik Kumar
              Room: Ballroom I

LW2   **Plasma Modelling I**
              Thomas Mussenbrock
              Room: Ballroom II

LW3   **Biomedical Applications I**
              Michael Keidar
              Room: Nassau Room

LW5   **Heavy-Particle Collisions**
              David Schultz, Michael S. Pindzola
              Room: Village Square

08:00 THURSDAY MORNING
03 OCTOBER 2013

MR1   **Poster Session III (8:00-9:30AM)**
              Room: Ballroom Foyer

10:00 THURSDAY MORNING
03 OCTOBER 2013

NR1   **Diagnostics I**
              Jan Schäfer
              Room: Ballroom I

NR2   **Plasma-surface Interactions**
              Room: Ballroom II

NR3   **Plasma Boundaries: Sheaths,**
              Boundary Layers, Others
              Mark Sobolewski, Dmytro
              Sydorenko
              Room: Nassau Room

13:30 THURSDAY AFTERNOON
03 OCTOBER 2013

PR1   **High Pressure Discharges:**
              Dielectric Barrier Discharges,
              Coronas, Breakdown, Sparks III
              Hirotaka Toyoda
              Room: Ballroom I

PR2   **Capacitively Coupled Plasmas I**
              Room: Ballroom II

PR3   **Gas Phase Plasma Chemistry**
              Room: Nassau Room

PR5   **Electron Collisions with Atoms and Molecules I**
Oleg Zatsarinny, Hari Chaluvadi
Room: Village Square

SF3   **Biomedical Applications II**
Room: Nassau Room

SF5   **Electron Collisions with Atoms and Molecules II**
Ali Belkacem
Room: Village Square

15:30 THURSDAY AFTERNOON 03 OCTOBER 2013

QR1   **Microwave Discharges II**
Room: Ballroom I

QR2   **Capacitively Coupled Plasmas II**
Trevor Lafleur
Room: Ballroom II

QR3   **Magnetically Enhanced Plasmas**
Teresa de los Arcos
Room: Nassau Room

10:30 FRIDAY MORNING 04 OCTOBER 2013

TF1   **Diagnostics II**
Thomas Schwarz-Selinger
Room: Ballroom I

TF2   **Low Pressure Plasma Modeling II**
Miles Turner, Vladimir Kolobov
Room: Ballroom II

19:00 THURSDAY EVENING 03 OCTOBER 2013

RR1   **Reception/Banquet**
Room: Ballroom

TF3   **Thermal Plasmas, Negative Ion Plasmas, and Dusty Plasmas**
Room: Nassau Room

TF5   **Electron-Molecule Collisions**
Thomas Rescigno, Steven Guberman
Room: Village Square

08:30 FRIDAY MORNING 04 OCTOBER 2013

SF1   **Plasmas for Nanotechnologies**
R. Mohan Sankaran
Room: Ballroom I

13:30 FRIDAY AFTERNOON 04 OCTOBER 2013

SF2   **Plasma Deposition**
Toshiaki Kato
Room: Ballroom II

UF1   **Scientific Legacy of Arthur Phelps**
Room: Ballroom I

SESSION AM1: WORKSHOP ON PLASMA SURFACE INTERACTION: FROM FUSION TO SEMICONDUCTOR PROCESSING
Monday Morning, 30 September 2013
Room: Ballroom I at 8:00
Yevgeny Raitses; Vincent Donnelly; David Graves; Greg DeTemmerman, PPPL; University of Houston; UC Berkeley; FOM Institute DIFFER, presiding

Contributed Papers

8:00
AM1 1 Welcome Y. RAITSES, *PPPL*

8:05
AM1 2 Challenges of Low Temperature Plasma-Surface Interactions DAVID GRAVES, *UC Berkeley* Low temperature plasma-surface interactions are characterized by complex, coupled interactions of chemical, physical and material phenomena interacting over a wide range of time and length scales. Intriguingly, some of the same kinds of challenges exist in non-low temperature plasma applications, including fusion-wall interactions. In this talk, I will review some of the history of low temperature plasma-surface studies and suggest some grand challenges in this interdisciplinary field. Examples will be presented from plasma-semiconductor surface interactions with an industrial focus. The latest applications of low temperature plasma involve plasma-soft material interactions, in some cases including the presence of water. The developing field of low temperature plasma medicine includes plasma-living tissue interactions. Some of the unique challenges posed by this new field will be briefly addressed.

8:35
AM1 3 The Science and Technology Challenges of the Plasma-Material Interface for Magnetic Fusion Energy* DENNIS WHYTE, *MIT - Plasma Science and Fusion Center* The boundary plasma and plasma-material interactions of magnetic fusion devices are reviewed. The boundary of magnetic confinement devices, from the high-temperature, collisionless pedestal through to the surrounding surfaces and the nearby cold high-density collisional plasmas, encompasses an enormous range of plasma and material physics, and their integrated coupling. Due to fundamental limits of material response the boundary will largely define the viability of future large MFE experiments (ITER) and reactors (e.g. ARIES designs). The fusion community faces an enormous knowledge deficit in stepping from present devices, and even ITER, towards fusion devices typical of that required for efficient energy production. This deficit will be bridged by improving our fundamental science understanding of this complex interface region. The research activities and gaps are reviewed and organized to three major axes of challenges: power density, plasma duration, and material temperature. The boundary can also be considered a multi-scale system of coupled plasma and material science regulated through the non-linear interface of the sheath. Measurement, theory and modeling across these scales are reviewed, with a particular emphasis on establishing the use dimensionless parameters to understand this complex system. Proposed technology and science innovations towards solving the PMI/boundary challenges will be examined.

*Supported by US DOE award DE-SC00-02060 and cooperative agreement DE-FC02-99ER54512.

9:05
AM1 4 Plasma Surface Interactions at a "Spinning Wall"* VINCENT M. DONNELLY, *University of Houston* Reactions of neutral species on surfaces immersed in plasmas have been recognized for many years to be important in affecting the chemistry of plasma processes such as plasma etching and chemical vapor deposition. The reactions of radicals on the surfaces of chamber walls and substrates are a sink for radicals and a source of larger product species. This talk will discuss a method for studying these processes in near-real-time. The surface of a rapidly rotating cylindrical substrate placed between the plasma chamber wall and a differentially pumped diagnostic chamber is continuously exposed to the plasma and then analyzed. Products desorbing from the surface a few milliseconds after exposure to the plasma are detected by line-of-sight mass spectrometry, while the surface is monitored with Auger electron spectroscopy. Kinetics of surface reactions can be extracted from an analysis of the signal intensities as a function of substrate rotation frequency. Examples of recombination of Cl and O atoms in chlorine and oxygen plasmas will be discussed. Possible applications of this method to studies plasma-surface interactions under harsher conditions, including at the edge of magnetic fusion devices, will be discussed.

*Work supported by the National Science Foundation, the Department of Energy, and Lam Research Corp.

9:35
AM1 5 Coffee Break

9:50
AM1 6 Determining atom and radical surface recombination coefficients in low-pressure plasmas* JEAN-PAUL BOOTH, *LPP-CNRS* In many low-pressure plasma processing applications (such as plasma etching), the dominant loss process for reactive atoms and free radicals is recombination at the reactor walls. This process is usually quantified by a phenomenological surface reaction coefficient, β, varying between 0 and 1, which is a crucial parameter for plasma modelling. As no reliable ab-initio theory exists to estimate the value of β for real surfaces, and as it may vary depending on the prevalent conditions, it must be measured in-situ. The simplest and most widespread technique is to determine the lifetime of the species in question in the afterglow of a pulsed plasma. The species density can be measured as a function of time using various methods including laser-induced fluorescence and time-resolved optical emission spectroscopy, and the coefficient is then derived using a diffusion model. This has been applied to many atoms (H, O, Cl, . . .) and free radicals (CF, CF_2, ...) This method necessarily assumes that the coefficient is unchanged in the afterglow, which may be questionable. Furthermore, if the gas temperature in the steady state plasma is significantly above that of the walls, the temperature will vary in the afterglow period, and may even cause gas convection, making analysis difficult. An alternative is to measure the density gradient adjacent to the surface in the steady state. The pros and cons of these methods will be discussed with examples of measurements.

*Work supported by Agence Nationale de la Recherche project INCLINE (ANR-09 BLAN 0019) and by the Applied Materials University Research Partnership Program.

10:20
AM1 7 Low Temperature Plasma Surface Interactions: Atomic Layer Etching And Atmospheric Pressure Plasma Jet Modification Of Biomaterials* GOTTLIEB OEHRLEIN, *Materials*

Science and Engineering, Institute for Research in Electronics and Applied Physics, University of Maryland, College Park, MD 20742-2115 Control of plasma-surface interactions is essential for successful application of low temperature plasma to materials processing. We review work performed in our laboratory in two areas: First, low pressure plasma surface interaction mechanisms aimed at achieving atomic precision in etching materials in the semiconductor industry. We discuss sequential reactions of surface passivation followed by directional low energy ion attack for "volatile product" removal to establish for what conditions self-limiting behavior required for Atomic Layer Etching (ALE) can be established using prototypical SiO_2 –Si/fluorocarbon-Ar materials/etching systems. Second, studies of plasma-surface interactions related to application of a non-equilibrium atmospheric pressure plasma jet (APPJ) for modification of biomaterials are discussed. Changes in surface chemistry/biological activity of lipopolysaccharide (LPS) exposed to the APPJ plume/effluent in a controlled environment are reviewed. The results clarify how jet chemistry and interactions of plasma with the environment impact the consequences of APPJ-biomaterial-surface interactions.

*Based on collaborations with D. Metzler, S. Engelmann, R. Bruce, E. Joseph, E. Bartis, C. Hart, Q.-Y. Yang, J. Seog, T.-Y. Chung, H.-W. Chang, and D.B. Graves. We gratefully acknowledge funding from US Department of Energy (DE-SC0005105; DE-SC0001939) and National Science Foundation (CBET-1134273; PHY-1004256).

10:50
AM1 8 Plasma-surface interactions under extreme conditions: challenges and opportunities GREGORY DE TEMMERMAN, *FOM Institute DIFFER* In a fusion reactor, power from the hot core plasma has to be exhausted by the plasma-facing components which are exposed to extreme heat ($>10MW.m^{-2}$) and particle fluxes (up to $10^{24}m^{-2}s^{-1}$ or $1.6\times10^5A.m^{-2}$)- orders of magnitude higher than in conventional plasma processing technique. Much of the fundamentals of the materials behaviour under such extreme ion irradiation conditions is not yet fully understood and limits our ability to develop materials able to survive those conditions. Combining a high efficiency plasma source and a strong magnetic field, linear plasma devices (LPD) allow to reproduce and even exceed the conditions expected in a fusion reactor. Owing to the good access to the plasma-material interaction zone for diagnostics and sample manipulation, those devices allow advanced experiments necessary to the fundamental understanding of plasma-surface interactions. In addition, the ion flux is such that a direct comparison with MD modelling, traditionally hampered by the large gap between fluxes in model and experiments, is now possible. This presentation will give an overview of the research performed to understand materials behaviour under extreme conditions with a focus on irradiation-driven modifications of metals. In parallel, the non-equilibrium conditions induced by the surface bombardment by extreme fluxes of low-energy particles open a novel route for the synthesis of advanced nanostructured materials, an illustration of which will be given.

11:20
AM1 9 Understanding plasma facing surfaces in magnetic fusion devices* C.H. SKINNER, A.M. CAPECE, *PPPL* B.E. KOEL, J.P. ROSZELL, *Princeton University* The plasma-material interface is recognized to be the most critical challenge in the realization of fusion energy. Liquid metals offer a self-healing, renewable interface that bypasses present issues with solid, neutron-damaged materials such as tungsten. Lithium in particular has dramatically improved plasma performance in many tokamaks through a reduction of hydrogen recycling. However the detailed chemical composition and properties of the top few nm that interact with the plasma are often obscure. Surface analysis has proven to be a key tool in semiconductor processing and a new laboratory has been established at PPPL to apply surface science techniques to plasma facing materials. We have shown that lithiated PFC surfaces in tokamaks will likely be oxidized during the intershot interval. Present work is focused on deuterium uptake of solid and liquid metals for plasma density control and sub-micron scale wetting of liquid metals on their substrates. The long-term goal is to provide a material database for designing liquid metal plasma facing components for tokamaks such as National Spherical Torus Experiment-Upgrade (NSTX-U) and Fusion Nuclear Science Facility-ST (FNSF-ST).

*Support was provided through DOE-PPPL Contract Number is DE-AC02-09CH11466.

11:50
AM1 10 Lunch

12:50
AM1 11 Interplay between discharge physics, gas phase chemistry and surface processes in hydrocarbon plasmas KHALED HASSOUNI, *CNRS, Universite Paris 13* In this paper we present two examples that illustrate two different contexts of the interplay between plasma-surface interaction process and discharge physics and gas phase chemistry in hydrocarbon discharges. In the first example we address the case of diamond deposition processes and illustrate how a detailed investigation of the discharge physics, collisional processes and transport phenomena in the plasma phase make possible to accurately predict the key local-parameters, i.e., species density at the growing substrate, as function of the macroscopic process parameters, thus allowing for a precise control of diamond deposition process. In the second example, we illustrate how the interaction between a rare gas pristine discharge and carbon (graphite) electrode induce a dramatic change on the discharge nature, i.e., composition, ionization kinetics, charge equilibrium, etc., through molecular growth and clustering processes, solid particle formation and dusty plasma generation. Work done in collaboration with Alix Gicquel, Francois Silva, Armelle Michau, Guillaume Lombardi, Xavier Bonnin, Xavier Duten, CNRS, Universite Paris 13.

13:20
AM1 12 Plasma-Surface Interaction in Presence of Intense Electron Emission from Walls* I.D. KAGANOVICH, E.A. STARTSEV, Y. RAITSES, H. WANG, M.D. CAMPANELL, A.V. KHRABROV, *Princeton Plasma Physics Laboratory, Princeton, NJ* A.N. ANDRONOV, A.S. SMIRNOV, *State Polytechnic University, St. Petersburg, Russia* D. SYDORENKO, *University of Alberta, Canada* V.I. DEMIDOV, *West Virginia University, Morgantown, WV* The plasma-surface interaction in presence of strong thermionic or secondary electron emission has been studied theoretically and experimentally both as a basic phenomenon and in relation to numerous plasma applications such as, divertor plasma, particle accelerators, surface discharges, plasma thrusters and plasma processing [1–3]. Secondary electron emission (SEE) from walls can be induced by electron or ion impact. The SEE can greatly alter the plasma-wall interaction and modify the whole structure of the plasma and its stability. A review of present theoretical models and experimental methods of investigating emission properties of different materials will be given. We also review a recently proposed

effect that the reflectivity of very low energy electrons from solid surface approaches unity in the limit of zero electron energy [2]. We report on recent experimental and particle-in-cell simulation studies on plasma-surface interaction in presence of electron emission [3,4].

*This work is supported by the US Department of Energy.

[1] J. Cazaux. J. Appl. Phys. **111**, 064903 (2012).
[2] R. Cimino, I. R. Collins Appl. Surface Scie. **235**, 231 (2004).
[3] Y. Raitses *et al.*, IEEE Trans. on Plasma Scie. **39**, 995 (2011).
[4] M. D. Campanell *et al.*, Phys. Rev. Lett. **108**, 235001 and 255001 (2012).

13:50

AM1 13 Behaviors of Hydrogen, Helium and their Synergy in Tungsten GUANG-HONG LU, *School of Physics & Nuclear Energy Engineering, Beihang University, Beijing 100191, China* Tungsten (W) is one of the most promising plasma facing material (PFM) candidates for fusion energy systems. However, effects of hydrogen (H) isotopes and helium (He) particularly their retention and blistering in W remain to be key issues that need to be addressed. In this talk, we will discuss the effects of H and He in W in terms of the physical mechanism revealed by simulations in combination with related experiments. Via modelling and simulation in different scales, the nucleation and growth mechanism of H bubbles in W have been investigated. First-principles calculations show that a vacancy induces collective H binding on its internal surface. Further calculations suggest a cascading effect of H bubble growth in W. Based on such vacancy trapping mechanism, He as well as other inert gas elements such as neon and argon can suppress the H bubble nucleation and blistering, which is confirmed by the experimental observation. Difference between H and He behaviors and their synergy in W due to their different electronic structure will be emphasized, from which we can further consider the actual complicated H/He interaction with W and their effects on (mechanical) properties of W in future fusion reactors.

14:20

AM1 14 Coffee Break

14:35

AM1 15 Challenges in Modeling of the Plasma-Material Interface* PREDRAG KRSTIC, *University of Tennessee* FRED MEYER, *Oak Ridge National Laboratory* JEAN PAUL ALLAIN, *Purdue University* Plasma-Material Interface mixes materials of the two worlds, creating a new entity, a dynamical surface, which communicates between the two and represent one of the most challenging areas of multidisciplinary science, with many fundamental processes and synergies. How to build an integrated theoretical-experimental approach? Without mutual validation of experiment and theory chances very slim to have believable results? The outreach of the PMI science modeling at the fusion plasma facilities is illustrated by the significant step forward in understanding achieved recently by the quantum-classical modeling of the lithiated carbon surfaces irradiated by deuterium, showing surprisingly large role of oxygen in the deuterium retention and erosion chemistry. The plasma-facing walls of the next-generation fusion reactors will be exposed to high fluxes of neutrons and plasma-particles and will operate at high temperatures for thermodynamic efficiency. To this end we have been studying the evolution dynamics of vacancies and interstitials to the saturated dpa doses of tungsten surfaces bombarded by self-atoms, as well as the plasma-surface interactions of

the damaged surfaces (erosion, hydrogen and helium uptake and fuzz formation).

*PSK and FWM acknowledge support of the ORNL LDRD program.

15:05

AM1 16 Plasma-Surface Interactions in Electric Thrusters DAN GOEBEL, *Jet Propulsion Laboratory, California Institute of Technology* Of critical importance in electric propulsion missions in space is thruster life, which is determined to a large extent by wall erosion from plasma-materials interactions. While the plasmas generated in different thrusters vary, the particle fluxes, energies and temperatures in contact with the walls are somewhat similar. The erosion rates are then determined by details of materials, incident angles, etc. In ion and Hall thrusters commonly used today, for example, cathode life is determined by low energy ($\leqslant 100$ eV) Xe ion erosion of the cathode electrodes. Erosion of ion thruster accelerator grids is dominated by charge exchange ion bombardment with energies of 200 to 400 V. The incident angle of these ions is near normal, but the sputtered particles are ejected with a butterfly distribution that directs particles along the thruster axis and causes build up of material on the upstream and downstream surfaces. In Hall thrusters, the plasma materials interactions at the wall are complicated because the walls are typically ceramic and selected for a low secondary electron yield for thruster performance. The erosion rates at the wall vary due to non-uniform plasma contact with the surface causing grooves and surface changes. These effects will be discussed for various thrusters.

15:35

AM1 17 Atmospheric Pressure Plasmas Incident onto Thin Liquid Layers* WEI TIAN, SETH NORBERG, NATALIA YU. BABAEVA, MARK J. KUSHNER, *University of Michigan* The interaction of plasmas with liquids has increasing importance in advanced manufacturing and biomedical applications. Sustaining atmospheric pressure plasmas *on liquids* (as opposed to *in liquids*) can increase the chemical activity of the liquid by transferring more easily produced reactive species from the gas phase into the liquid. Often the intent is to treat the surface under the liquid layer, as in plasma medicine. The liquid then acts as a filter which modifies the fluxes of reactive species prior to reaching the underlying surface. The liquid in turn influences the plasma by evaporation which produces a saturated layer of, for example, water vapor above the liquid surface, or by the shape of liquid covered wounds and the dielectric properties of the liquid. Direct plasma exposure (e.g., a dielectric barrier discharge) enables intersection of ion and UV/VUV fluxes with the liquid surface whereas many remote plasma jets typically do not. This increases the rate of hydronium (H_3O^+) production which affects pH. In this paper, results from a computational investigation on the dynamics of atmospheric pressure plasmas intersecting thin water layers having dissolved gases and proteins will be discussed. Examples are taken from DBD and plasma jet exposure of water layers over a tissue-like dielectric, and plasmas sustained in bubbles in water. The mutual interaction of the plasma and liquid will be discussed based on radiation and ion transport into the water, evaporation, and transport and conversion of plasma produced reactivity through the water layer.

*Work supported by DOE Fusion Energy Science and NSF.

16:05
AM1 18 Roundtable Discussion Moderators: Michael A. Lieberman of UC Berkley and Russel Doerner of UC San Diego.

SESSION AM2: WORKSHOP ON WEAKLY-IONIZED NON-EQUILIBRIUM AIR PLASMA AT MODERATE AND HIGH PRESSURES: GENERATION AND MAINTENANCE, MODELING, DIAGNOSTICS AND APPLICATIONS
Monday Morning, 30 September 2013
Room: Ballroom II at 8:30
Mikhail Shneyder; Richard Miles, Princeton University, presiding

Contributed Papers

8:30
AM2 1 WELCOME

8:35
AM2 2 Plasma-Based Mixing Actuation in Airflow, Quantitated by Probe Breakdown Fluorescence* SERGEY LEONOV, *Ohio State University* ALEXANDER FIRSOV, MICHAIL SHURUPOV, DMITRY YARANTSEV, *JIHT RAS* OHIO STATE UNIVERSITY TEAM, JIHT RAS TEAM Effective mixing of fuel and oxidizer in air-breathing engine at compressible conditions is an essential problem of high-speed combustion due to short residence time of gas mixture in the combustor of limited length. The effect of the mixing actuation by plasma is observed because of the gasdynamic instability arisen after the long filamentary discharge of submicrosecond duration generated along the contact zone of two co-flown gases. The work is focused on detail consideration of the mechanism of gas instability, promoted by plasma, on effect of the discharge specific localization, and on diagnostics development for qualitative and quantitative estimation of the mixing efficiency. The dynamics of relative concentration of gas components is examined quantitatively by means of Probe Discharge Breakdown Fluorescence (PBF). In this method an optical emission spectra of weak filamentary high-voltage nanosecond probe discharge are collected from local zone of interest in airflow. The first measurements of the mixing efficiency in vicinity of wall-injected secondary gas are presented. It is shown that the method of PBF could deliver experimental data on state of the two-component medium with <1 mcs and <5 mm of time and spatial resolution, correspondingly.

*Funded by AFOSR under Dr Chiping Li supervision

9:05
AM2 3 Towards fully hybrid simulations of atmospheric pressure plasmas ALEXANDRE LIKHANSKII, *Tech-X Corporation* Recent experimental studies demonstrated high potential of using atmospheric pressure plasmas for a number of industrial application, such as plasma medicine, plasma processing, plasma aerodynamics and plasma transistors. Majority of the numerical efforts addressing this type of gas discharges were done using fluid plasma representation. However, fluid plasma models lack important plasma effects, such as non-Maxwellian EEDF in the cathode sheath of streamer head or formation of filamentary structures. These effects must be addressed using kinetic approach. The presentation will describe the developed hybrid (kinetic+fluid) model in Tech-X code VSim (formerly Vorpal) for simulation of wide range of discharges. The model incorporated majority of relevant physics processes, including photoionization for accurate description of filament development. The results of the simulation of atmospheric pressure discharges for relevant industrial problems using kinetic, fluid and hybrid approaches will be presented, and detailed comparison between the models will be provided.

9:35
AM2 4 BREAK

9:50
AM2 5 Advanced laser diagnostics for gases and weakly ionized plasma ARTHUR DOGARIU, *Princeton University* Recent advancements in laser-based gas and plasma diagnostics will be presented, ranging from resonant multiphoton ionization to femtosecond filamentation. Spectroscopy and remote trace gas detection down to parts-per-billion are demonstrated using a combination of resonant laser ionization through multiphoton excitation, and microwave scattering off the weakly ionized plasma. The Radar-REMPI (Resonantly Enhanced Multi-Photon Ionization) technique also allows for studying the dynamics of the weak plasma, and first direct measurements of the electron attachment rates in atmospheric air are demonstrated. The plasma dynamics not only reveals the electron loss mechanisms such as attachment and recombination, but can also be a good measure of the electron density. Laser based techniques such as Rayleigh scattering are used for gas temperature measurements, and in particular Filtered Rayleigh Scattering shows great promise in environments where background scattering is significant. Femtosecond Laser Electronic Excitation Tagging (FLEET) is a new non-invasive laser technique for flow velocity mapping, and it is based on imaging nitrogen emission in femtosecond filaments. FLEET has been recently proven to be adequate for measuring and mapping the gas temperature as well.

10:20
AM2 6 Physical and biological mechanisms of nanosecond- and microsecond-pulsed FE-DBD plasma interaction with biological objects DANIL DOBRYNIN, *Drexel Plasma Institute* Mechanisms of plasma interaction with living tissues and cells can be quite complex, owing to the complexity of both the plasma and the tissue. Thus, unification of all the mechanisms under one umbrella might not be possible. Here, analysis of interaction of floating electrode dielectric barrier discharge (FE-DBD) with living tissues and cells is presented and biological and physical mechanisms are discussed. In physical mechanisms, charged species are identified as the major contributors to the desired effect and a mechanism of this interaction is proposed. Biological mechanisms are also addressed and a hypothesis of plasma selectivity and its effects is offered. Spatially uniform nanosecond and sub-nanosecond short-pulsed dielectric barrier discharge plasmas are gaining popularity in biological and medical applications due to their increased uniformity, lower plasma temperature, lower surface power density, and higher concentration of the active species produced. In this presentation we will compare microsecond pulsed plasmas with nanosecond driven systems and their applications in biology and medicine with specific focus on wound healing and tissue regeneration. Transition from negative to positive streamer will be discussed with proposed hypothesis of uniformity mechanisms of positive streamer and the reduced dependence on morphology and surface chemistry of the second electrode (human body) being treated. Uniform plasma offers a more uniform delivery of active species to the tissue/surface being treated thus leading to better control over the biological results.

10:50

AM2 7 Surface Wave Driven Air-Water Plasmas* ELENA TATAROVA, JULIO HENRIQUES, CARLOS FERREIRA, *Institute of Plasmas and Nuclear Fusion, Instituto Superior Tecnico, Technical University of Lisbon, Portugal* The performance of a surface wave driven air-water plasma source operating at atmospheric pressure and 2.45 GHz has been analyzed. A 1D model has been developed in order to describe in detail the creation and loss processes of active species of interest and to provide a complete characterization of the axial structure of the source, including the discharge and the afterglow zones. The main electron creation channel was found to be the associative ionization process $N+O \rightarrow NO^+ + e$. The NO(X) relative density in the afterglow plasma jet ranges from 1.2% to 1.6% depending on power and water percentage according to the model predictions and the measurements. Other types of species such as NO_2 and nitrous acid HNO_2 have also been detected by mass and FT-IR spectroscopy. Furthermore, high densities of $O_2(a^1\Delta_g)$ singlet delta oxygen molecules and OH radicals (1% and 5%, respectively) can be achieved in the discharge zone. In the late afterglow the $O_2(a^1\Delta_g)$ density is about 0.1% of the total density. The plasma source has a flexible operation and potential for channeling the energy in ways that maximize the density of active species of interest.

11:20

AM2 8 RF discharge phenomena in miniaturized RF MEMS cavity-based filters DIMITRIOS PEROULIS, *Purdue University* Reconfigurable filters are critical devices for the coming generation of high-frequency electronics. Several competing requirements including miniaturization, performance, frequency-agility and power handling need to be carefully considering in designing successful filters particularly for mobile-form-factor electronics. This talk will discuss the latest findings in state-of-the-art tunable cavity-based RF MEMS filters as relate to the aforementioned factors. Special attention will be paid on the role that RF gas discharge phenomena play in the performance and lifetime of these devices.

11:50
AM2 9 LUNCH

12:50

AM2 10 High pressure noble gas plasmas in microcavities: a review of the discharge physics SERGEY MACHERET, *Lockheed Martin Aeronautics Company* High pressure (from tens to hundreds of Torr) inert gas plasmas confined in microcavities are studied because of both applications and interesting physics. The presentation is a review of research literature on this topic, focusing on the dynamics of electric discharges in microcavities.

13:20

AM2 11 SI Engine with repetitive NS spark plug SERGEY PANCHESHNIY, *LAPLASE* ANDREY NIKIPELOV, EUGENY ANOKHIN, *Moscow Institute of Physics and Technology* ANDREY STARIKOVSKIY, *Princeton University* LAPLASE TEAM, MIPT TEAM, PU TEAM Now de-facto the only technology for fuel-air mixtures ignition in IC engines exists. It is a spark discharge of millisecond duration in a short discharge gap. The reason for such a small variety of methods of ignition initiation is very specific conditions of the engine operation. First, it is very high-pressure of fuel-air mixture – from 5-7 atmospheres in old-type engines and up to 40-50 atmospheres on the operating mode of HCCI. Second, it is

a very wide range of variation of the oxidizer/fuel ratio in the mixture – from almost stoichiometric (0.8-0.9) at full load to very lean ($\varphi = 0.3$-0.5) mixtures at idle and/or economical cruising mode. Third, the high velocity of the gas in the combustion chamber (up to 30-50 m/s) resulting in a rapid compression of swirling inlet flow. The paper presents the results of tests of distributed spark ignition system powered by repetitive pulse nanosecond discharge. Dynamic pressure measurements show the increased pressure and frequency stability for nanosecond excitation in comparison with the standard spark plug. Excitation by single nanosecond high-voltage pulse and short train of pulses was examined. In all regimes the nanosecond pulsed excitation demonstrate a better performance.

14:20

AM2 13 Characteristics of short dc glow microdischarges in atmospheric pressure air* ANATOLY KUDRYAVTSEV, *St. Petersburg State University* The main reason that high pressure current-carrying plasmas tend to be unstable is various instability (primarily thermal) of the positive column (PC). So a promising approach is to use short (without PC) discharges that have growing voltage–current characteristic (VAC). These discharges are ignited near the minimum of the Paschen breakdown curve *Lmin* and it usually have a gap *pL <10–20 cm Torr* when a distinct PC is absent. In this report the most stable microdischarges were burning with a flat cathode and rounded (or thin rod) anode, which located to a distance less than *Lmin* when the microdischarge "choose" their length itself, so that to match the stable work near *Lmin* by changing their binding on the anode. For simulations we used 2D hybrid model. Simulations predicted the main regions of the dc glow discharges including cathode and anode sheath and plasma of negative glow, Faraday dark space and transition region, in which the electric field is distributed no uniformly and plasma is nonlocal. Gas heating plays an important role in shaping the discharge profiles.

14:50

AM2 14 High-Voltage Nanosecond Pulse Action on RF Discharge LEONID VASILYAK, *Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow* MIKHAIL PUSTYLNIK, *Max-Planck-Institut fur Extraterrestrische Physik, Garching, Germany* LUJING HOU, ALEXEI IVLEV, *Max-Planck-Institut fur Extraterrestrische Physik, Germany* LENAIC COUEDEL, *Aix-Marseille-Universite, France* HUBERTUS THOMAS, GREGOR MORFILL, *Max-Planck-Institut fur Extraterrestrische Physik, Germany* VLADIMIR FORTOV, *Joint Institute for High Temperatures, Russian Academy of Sciences* After the discharge of atmospheric lightning from cloud to the ground the space electric charge appears. We investigated experimentally similar situation in a short discharge gap. A high-voltage (3-17 kV) 20 ns pulse was applied to the weakly-ionized RF discharge. The plasma evolution exhibits two regimes: a bright flash, occurring within 100 ns after the pulse, and a dark phase, lasting a few hundreds microseconds. Electron density increased during the flash remains high during the dark phase. 1D3V particle-in-cell simulation was made. The high-voltage nanosecond pulse is found to be capable of removing a significant fraction of plasma electrons out of the discharge gap. The flash is the result of the excitation of gas by the electron in the residual electric field of the bulk positive charge. High density plasma formed during the flash provides screening of the steady-state RF field, which leads to the electron cooling and, hence, a dark phase.

15:20
AM2 15 BREAK

15:35
AM2 16 Nanosecond Glow and Spark Discharges in Ambient Air and in Water Vapor* CHRISTOPHE LAUX, DIANE RUSTERHOLTZ, FLORENT SAINCT, DA XU, DEANNA LACOSTE, GABI STANCU, *EM2C Laboratory, CNRS - Ecole Centrale Paris* DAVID PAI, *PPRIME Institute (CNRS - University of Poitiers - ENSMA)* Nanosecond repetitively pulsed (NRP) discharges are one of the most energy efficient ways to produce active species in atmospheric pressure gases. In both air and water vapor, three discharge regimes can be obtained: 1) corona, with light emission just around the anode, 2) glow, corresponding to a diffuse nonequilibrium plasma, and 3) spark, characterized by higher temperatures and higher active species densities. The glow regime was initially obtained in air preheated at 2000 K. Based on a model defining the transition between glow and spark, we recently succeeded in obtaining a stable glow in ambient air at 300 K, using a judicious combination of electrode geometry, pulse duration, pulse frequency, and applied voltage. We will present these results and describe the characteristics of the discharge obtained in room air. The spark regime was also studied. NRP sparks induce ultrafast gas heating (about 1000 K in 20 ns) and high oxygen dissociation (up to 50% dissociation of O_2). This phenomenon can be explained by a two-step process involving the excitation of molecular nitrogen followed by exothermic dissociative quenching of molecular oxygen. The characteristics of NRP discharges in water vapor will also be discussed.

16:05
AM2 17 ROUND TABLE DISCUSSION Moderators: Michael A. Lieberman of UC Berkley; Russel Doerner of UC San Diego.

SESSION BM1: WELCOME RECEPTION
Monday Evening, 30 September 2013
Room: Ballroom Foyer at 18:00

Contributed Papers

18:00
BM1 1 Welcome Reception

SESSION CT1: POSTER SESSION I (8:00-9:30AM)
Tuesday Morning, 1 October 2013
Exhibit Ballroom Foyer at 8:00

CT1 1 PLASMA SCIENCE

CT1 2 Experimental observation of dust ion acoustic wave propagation in a negative ion rich dusty plasma NIRAB CHANDRA ADHIKARY, HEREMBA BAILUNG, *Institute of Advanced Study in Science and Technology* PLASMA PHYSICS LABORATORY TEAM In the present work nonlinear propagation of dust ion-acoustic (DIA) solitary waves (SWs) in a negative ion rich dusty plasma is experimentally investigated. The effect of negative ions on the formation of rarefactive solitary wave in a dusty double plasma device is observed and its characteristics are analyzed. The important observation in this work is that; for the present dusty plasma condition, the applied electric perturbation cannot form a train of rarefactive solitons while propagating, until a sufficient amount of negative ions is introduced into the dusty plasma. It is also observed that the viscosity in the dusty plasma plays a crucial role in the formation and dissipation of solitary waves. The velocity and width of the solitary waves are measured and compared with numerical results obtained from the Korteweg–de Vries (K-dV) Burgers equation.

CT1 3 Afterglow Behavior of Laser-Breakdown Atmospheric Helium Plasmas E. NEDANOVSKA, D. RILEY, W.G. GRAHAM, *Queen's University, Belfast* L. HUWEL, T.J. MORGAN, *Wesleyan University* T. MURAKAMI, *Tokyo Institute of Technology* We present experimental and theoretical results on the temporal evolution of the electron density and temperature of a plasma formed by laser-induced breakdown in atmospheric helium. Plasma is created by a 9 ns, 140 mJ pulse from a Nd:YAG laser at 1064 nm and diagnosed with a separate laser using Thomson scattering with a 532 nm, 9 nm, 80 mJ probe beam during time delays ranging from 2 μs out to 22.5 μs. A zero-dimensional time-dependent global chemistry model is used to simulate the electron concentration, using pure helium and helium plus small amounts of humid air and molecular nitrogen. The effect of these small concentrations (1 ppm to 100 ppm) is significant and modifies the temporal decay behavior for both early and late times. Detailed analysis and comparisons with calculation will be presented at the conference.

CT1 4 NON-EQUILIBRIUM KINETICS OF LOW-TEMPERATURE PLASMAS

CT1 5 Kinetics of Charged Particles in CF CF$_4$ at High Values of Reduced Electric Field* ZORAN PETROVIC, VLADIMIR STOJANOVIC, NIKOLA SKORO, DRAGANA MARIC, ZORAN RASPOPOVIC, *Institute of Physics University of Belgrade, P.O.B. 68, 11080 Belgrade, Serbia* In this work we present results of our study of charged particle transport in dark Townsend discharges in CF$_4$ Monte Carlo technique, based on null collision method, already used for similar discharges in nitrogen, argon and hydrogen is used to obtain spatially resolved transport parameters for a range of reduced electric fields (E/N) from 700 Td to 20 kTd (1 Td $= 10^{-21}$ Vm^2). In this work we focus on anisotropic scattering of electrons and we also obtain a consistent set of cross sections for ions and

fast neutrals. Apart from the agreement of experimental and Monte Carlo results for electron and ion transport data, agreement with experimental results for spatially resolved optical emission and ionic energy distribution functions at high values of E/N is achieved.

CT1 6 PLASMA MODELING AND SIMULATION

CT1 7 Mitigating chromatic effects for the transverse focusing of intense charged particle beams* JAMES MITRANI, *PPPL, Princeton University* IGOR KAGANOVICH, *PPPL* RONALD DAVIDSON, *PPPL, Princeton University* A final focusing scheme designed to minimize chromatic effects is discussed. Solenoids are often used for transverse focusing in accelerator systems that require a charged particle beam with a small focal spot and/or large energy density A sufficiently large spread in axial momentum will reduce the effectiveness of transverse focusing, and result in chromatic effects on the final focal spot. Placing a weaker solenoid upstream of a stronger final focusing solenoid (FFS) mitigates chromatic effects on transverse beam focusing. J.M. Mitrani *et al.*, Nucl. Inst. Meth. Phys. Res. A (2013) http://dx.doi.org/10.1016/j.nima.2013.05.09

CT1 8 Semi-analytical modelling of positive corona discharge in air* FRANCISCO PONTIGA, *University of Seville* KHELIFA YANALLAH, *Université Ibn Khaldoun, Algeria* JUNHONG CHEN, *University of Wisconsin-Milwaukee, USA* Semianalytical approximate solutions of the spatial distribution of electric field and electron and ion densities have been obtained by solving Poisson's equations and the continuity equations for the charged species along the Laplacian field lines. The need to iterate for the correct value of space charge on the corona electrode has been eliminated by using the corona current distribution over the grounded plane derived by Deutsch, which predicts a $\cos^m \theta$ law similar to Warburg's law. Based on the results of the approximated model, a parametric study of the influence of gas pressure, the corona wire radius, and the inter-electrode wire-plate separation has been carried out. Also, the approximate solutions of the electron number density has been combined with a simplified plasma chemistry model in order to compute the ozone density generated by the corona discharge in the presence of a gas flow.

CT1 9 Collisional-radiative model for non-Maxwellian argon plasmas ALLAN STAUFFER, *Department of Physics and Astronomy, York University, Toronto, Canada* DIPTI GOYAL, *Department of Physics, Indian Institute of Technology, Roorkee, India* REETESH GANGWAR, *Départment de Physique, Université de Montréal, Montréal, Canada* RAJESH SRIVASTAVA, *Department of Physics, Indian Institute of Technology, Roorkee, India* We have applied our collisional radiative model [1] to inductively-coupled argon plasmas using a non-Maxwellian electron energy distribution function. We included detailed fine-structure cross sections calculated by our relativistic distorted-wave method as well as ionization processes to determine the population of the important excited levels of argon in the plasma for pressures in the range of 1-25 mTorr.

We will present detailed results of our calculations and compare these with recent measurements of Boffard *et al.* [2,3] including emission line ratios that can be used to determine plasma temperatures.

[1] R. K. Gangwar, L. Sharma, R. Srivastava, and A. D. Stauffer, J. Appl. Phys. **111**, 053307 (2012).

[2] J. B. Boffard, R. O. Jung, C. C. Lin, and A. E. Wendt, Plasma Sources Sci. Technol. **19**, 065001 (2010).

[3] J. B. Boffard, R. O. Jung, C. C. Lin, L. E. Aneskavich, and A. E. Wendt, J. Phy. D: Appl. Phys. **45**, 045201 (2012).

CT1 10 PIC Simulations of Atmospheric Pressure Capacitive RF He/N₂ Discharges*

E. KAWAMURA, M.A. LIEBERMAN, A.J. LICHTENBERG, *University of California, Berkeley* C. LAZZARONI, *Universite Paris 13* P. CHABERT, *Ecole Polytechnique* Atmospheric pressure rf micro-discharges have been extensively studied, due to emerging applications, particularly in medical and related areas. Because of their small size, diagnostics are difficult. A previous work studied discharges with a helium feed gas and small admixture of N_2 by using a 1D hybrid analytical-numerical model [1]. But this model did not consider sheath breakdown phenomena, thus limiting its applicability to the lower power range. To overcome this, we perform 1D particle-in-cell (PIC) simulations of atmospheric pressure capacitve RF He/N₂ discharges and use the results to guide the development of a model for the γ mode of the discharge. We noted from [1] that the dominant species in He/N₂ discharges with 0.1% N_2 were N_2^+ ions, electrons, and metastable helium atoms He*. This enabled us to develop a simplified cross-section set only involving those three species.

[1] C. Lazzaroni, P. Chabert, M. A. Lieberman, A. J. Lichtenberg, and A. Leblanc, Plasma Sources Sci. Technol. **21**, 035012 (2012).

CT1 11 Modeling and simulation of high current flowing through a vacuum arc interacting with electrodes and shields

KAI HENCKEN, JOSCHUA DILLY,* *ABB Switzerland Ltd., Corporate Research* Constricted vacuum arcs are typically found in specific vacuum interrupter types at high total currents. Such arcs are metal vapor arcs fed by the evaporation of material from the electrodes. In order to improve the performance of these breakers CFD simulations are an important tool. For a realistic simulation the conditions at the interface between the plasma and the electrodes are essential. This is the case especially at the arc roots, where high current densities occur. Here the microscopic processes of electron- and ion-flow into and out of the metal surface need to be taken into account; on the other hand the macroscopic current distribution is influenced by the current-voltage characteristic of this interface. In this contribution we present the physical model underlying the system of equations used for the plasma-electrode interface. In a second step these are implemented as boundary conditions for a simulation of the electric current distribution using a finite element approach. This is used as the basis to perform simulations of an vacuum arc interacting with a metal shield. A commutation of the current as a function of the surface temperature is found.

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CT1 12 Higher Performance of Photon-enhanced Thermionic Emission Energy Converter by Contact Ionization Rate Enhancement

HARUKI TAKAO, *Osaka University* MARK CAPPELLI, *Stanford University* TSUYOHITO ITO, *Osaka University* Traditionally, thermionic energy conversion is most efficient at high temperatures (> 1500 K). In a recent study [J.W. Schwede *et al.*, Nature Materials **9**, 762 (2010)], photon-enhanced thermionic emission (PETE) from semiconducting cathodes was shown to drastically increases the thermionically-driven cathode current density at relatively low cathode temperatures (500-1100 K). However, at the high emitted current densities (3 - 30 A/cm²) electron transport will be space charge limited. Last year (Bulletin of the American Physical Society, 57 (2012)), we demonstrated that using a particle-in-cell (PIC) method, continuous laser excitation of the cesium resonance level in a PETE thermionic discharge with cesium filling (resonance-enhanced PETE, or R-PETE) can suppress the space charge and boost the output current, to near ideal limits. In this presentation, we analyze the converter efficiency with an improved PIC simulation. The results suggest that increasing the probability of contact ionization on the semiconducting cathode surface may be a means of realizing the high efficiency and high current densities that an R-PETE converter can offer.

CT1 13 RF models for plasma-surface interactions*

THOMAS JENKINS, DAVID SMITHE, MING-CHIEH LIN, SCOTT KRUGER, PETER STOLTZ, *Tech-X Corporation* Computational models for DC and oscillatory (RF-driven) sheath potentials, arising at metal or dielectric-coated surfaces in contact with plasma, are developed within the VSim code and applied in parameter regimes characteristic of fusion plasma experiments and plasma processing scenarios. Results from initial studies quantifying the effects of various dielectric wall coating materials and thicknesses on these sheath potentials, as well as on the ensuing flux of plasma particles to the wall, are presented. As well, the developed models are used to model plasma-facing ICRF antenna structures in the ITER device; we present initial assessments of the efficacy of dielectric-coated antenna surfaces in reducing sputtering-induced high-Z impurity contamination of the fusion reaction.

CT1 14 Evolution and dynamics of charged aerosols in plasmas*

DECLAN DIVER, EUAN BENNET, HUGH POTTS, *University of Glasgow* CHARLES MAHONY, PAUL MAGUIRE, DAVIDE MARIOTTI, *University of Ulster* Understanding the evolutionary processes governing the dynamics and stability of charged macroscopic droplets in a discharge plasma is a central component of an innovative collaborative project on bacteria detection. Aerosolized bacteria samples will be injected into a discharge to acquire significant electrical charge. Two key aspects are then core to research: (i) the fluid stability of the charged aerosols under evaporative stress, and (ii) the stochastic component of their motion. (i) Initially stable charged aerosols subject to evaporation (continuously changing radius) may encounter the Rayleigh limit governing the maximum charge QR as a function of radius, arising from the electrostatic and surface tension forces. Additionally, the maximum surface field before charge emission QE can impose further constraints. (ii) A droplet is in any event subject to Brownian motion just like any other small particle, buffeted by a mixture of (dominant) neutrals and plasma, with the latter forming a sheath around the particle. The Brownian motion induced forces the sheath around the grain to move, incurring changes in impacting ion flux that can represent an additional drag term, changing the classical Brownian diffusion. We present analysis for a variety of discharge conditions.

CT1 15 Comparing fluid models for streamer discharges ARAM H. MARKOSYAN, JANNIS TEUNISSEN, *Centrum Wiskunde and Informatica, Amsterdam* SASHA DUJKO, *Institute of Physics University of Belgrade* UTE EBERT, *Centrum Wiskunde and Informatica, Amsterdam* Our recently developed high order fluid model, based on additional moments of the Boltzmann equation, for streamer discharges has shown excellent agreement with PIC/MC (Particle in cell/Monte Carlo) simulations in nitrogen. This motivates us to compare several commonly used fluid models for streamer discharges with the high order model. The fluid models considered in this work are: the first order model (also known as drift-diffusion-reaction, "minimal" or "classical" model), the first order model with an energy equation and the high order fluid model. As a reference we use PIC/MC simulations. We compare the models under STP conditions in argon, neon and nitrogen.

CT1 16 Coupled discretization of multicomponent diffusion problems in equilibrium and non-equilibrium plasmas KIM PEERENBOOM, JAN TEN THIJE BOONKKAMP, JAN VAN DIJK, GERRIT KROESEN, *Eindhoven University of Technology* Solving balance equations is the essence of any fluid simulation of reactive, multicomponent plasmas. For plasmas in chemical non-equilibrium, balance equations are solved for all species of interest. When reactions are very fast with respect to transport time scales – and the plasma approaches chemical equilibrium – species abundances can be obtained from equilibrium relations. However, in many cases, balance equations still need to be solved for the elements, since the elemental composition can vary significantly in reactive multicomponent plasmas. Both in equilibrium and in non-equilibrium the species diffusive fluxes in these balance equations are governed by the Stefan-Maxwell equations. The use of Stefan-Maxwell diffusion leads to a coupled set of balance equations. Furthermore, this coupled set of equations is subject to charge and mass conservation constraints. Due to these complications the set of balance equations is often artificially decoupled to fit in the traditional finite volume discretization schemes and the constraints are explicitly applied. This approach can lead to very poor convergence behavior. We will present a new approach using a finite volume discretization scheme that takes into account the coupling and treats the constraints implicitly.

CT1 17 Three-dimensional Modelling of Two-phase Flow involving Droplets and Atmospheric Pressure Discharge* M.M. IQBAL, *Dublin City University* C.P. STALLARD, D.P. DOWLING, *University College Dublin* M.M. TURNER, *Dublin City University* We employ a three-dimensional coupled fluid-droplet model (FD3d) to describe the complex mechanism of droplet-plasma interaction that occurs when a liquid precursor is injected through a nebulizer into an atmospheric pressure discharge (APD). The formation of conducting channels in the APD plasma illustrates that the electron concentration around the pulse of droplets emitted by the nebulizer is perturbed by the influence of different gas impurities due to the impact of Penning ionization. The development of the sheath potential around the pulse of HMDSO droplets is significantly stronger in the case of He-air than a He-N2 gas mixture, which illustrates the contribution of oxygen impurities. The volumetric density profiles of ionic species are discussed by describing the complex situation of two-phase flow at distinct driving frequencies (5 - 100 kHz). The uniform structure of APD plasma is formed by considering an appropriate size distribution of droplets because the non-uniformities grow due to the existence of larger radii of droplets. The comparison of numerical modelling results of droplet size distributions is performed with experimental measurements using laser diffraction particle size analysis technique. The desired properties of surface coating applications can be predicted by controlling various parameters mentioned in the fluid-droplet model.

CT1 18 Do dielectrics attract streamer discharges?* ANNA DUBINOVA, JANNIS TEUNISSEN, UTE EBERT, *Centrum Wiskunde & Informatica* MULTISCALE DYNAMICS TEAM Streamer discharges developing near dielectric materials can cause sparks and surface flashovers. This effect is to be avoided in high voltage technology. Dielectric materials tend to attract the discharge due to polarization effects resulting in the modification of the local electric field. Other mechanisms known for influencing streamer discharge propagation include photoionization, background ionization, accumulation of surface charge on the dielectrics and secondary electron emission. However, the actual physical mechanisms responsible for the surface flashovers are still under discussion. Developing advanced simulation tools, we aim at getting insight into the nature of streamer discharges in the presence of dielectrics in full 3D. We report the results of our simulations showing essential differences between a positive streamer propagating due to background ionization and due to photoionization. We compare our numerical results with experiments. We also describe a numerical method (a generalized Ghost Fluid Method) which allowed us to include dielectric interfaces into our streamer models, in an accurate and fast manner.

CT1 19 Phase Transformation of Droplets into Particles and Nucleation in Atmospheric Pressure Discharges* M.M. IQBAL, *Dublin City University* C.P. STALLARD, D.P. DOWLING, *University College Dublin* M.M. TURNER, *Dublin City University* We investigate the mechanism of phase transformation of liquid precursor droplets into nano-particulates in an atmospheric pressure discharge (APD). This phase transformation is possible when the solid to a liquid mass ratio of slurry droplet reaches a threshold value. The behaviour of phase transformation of a single slurry droplet of HMDSO is described by developing a numerical model under the saturation condition of evaporation. It is observed from the temporal evolution of inner radius (R_i) of a single slurry droplet that its value approaches zero before the entire shifting of a liquid phase and which explains with an expansion in the crust thickness ($R_o - R_i$). The solid traces of nano-particles are observed experimentally on the surface coating depositions because the time for transferring the slurry droplet of HMDSO into solid state is amplified with an increment in the radii of droplets and the entire phase transition occurs within residence time for the nano-sized liquid droplets. The GDE coupled with discharge plasma is numerically solved to describe the mechanism of nucleation of nano-sized particles in APD plasma under similar conditions of the experiment. The growth of nucleation in APD plasma depends on the type of liquid precursor, such as HMDSO, TEOS and water, which is verified with a sharp peak in the nucleation rate and saturation ratio.

CT1 20 Kinetic Analysis of High Pressure DC Microplasmas via a One-dimensional PIC-MCC Simulation HYONU CHANG, *National Fusion Research Institute* CHANG-MO RYU, *Pohang*

University of Science and Technology, Physics SUK JAE YOO, *National Fusion Research Institute* Characteristics of dc high pressure argon microplasmas are studied by using a one-dimensional particle-in-cell and Monte Carlo collision simulation. The accelerated electrons inside the cathode fall region rapidly lose their kinetic energy near the cathode due to a high collision rate, and forming a highly non-uniform electron distribution in the positive column. This non-uniformity creates a difference between the electron diffusion current density and drift current density in the negative glow and positive column. An electric field is built to sustain continuity of the total current density. This retards the electron diffusion current in the region where the electron density gradient is large and induces an electron drift current in the region where electron density gradient is small. When the electrode gap is very small for electrons to diffuse in the entire volume of discharge, only one field reversal is shown in the negative glow. The discharge at atmospheric pressure has a shorter length of the cathode fall, a more biased electron distribution to the cathode, and a stronger negative electric field between the second and third field reversals due to an increased collision rate compared with that at 300 Torr.

CT1 21 Molecular dynamics simulation analysis of ion irradiation effects on plasma-liquid interface* YUDAI MINAGAWA, NAOKI SHIRAI, SATOSHI UCHIDA, FUMIYOSHI TOCHIKUBO, *Tokyo Metropolitan University* Nonthermal atmospheric plasmas are used in a wide range of fields because the high-density plasma can be easily irradiated to various substances such as solid, liquid, biological object and so on. On the other hand, the mechanisms of physical and chemical phenomena at the plasma-liquid interface are not well understood yet. To investigate the effects of ion impact from plasma on water surface, we analyzed behavior of liquid water by classical molecular dynamics simulation. Simulation system consists of an irradiation particle in gas phase and 2000 water molecules in liquid phase. O^+ ion with 10 eV or 100 eV was impinged on the water surface. Ion impact induced increasing water temperature and ejection of water molecules. The averaged number of evaporated water molecules by ion impact is 0.6 molecules at 10 eV and 7.0 molecules at 100 eV. The maximum ion penetration depth was 1.14 nm at 10 eV and 2.75 nm at 100 eV. Ion entering into water disturbs the stable hydrogen bonding configurations between water molecules and gives energy to water molecules. Some water molecules rotated and moved by ion interaction impact on other water molecules one after another. When the water molecule near the surface received strongly repulsive force, it released into gas phase.

CT1 22 Transport Properties of Fluorine Ions in BF_3 VLADIMIR STOJANOVIC, ZORAN RASPOPOVIC, *Institute of Physics, University of Belgrade, Belgrade, Serbia* JASMINA JOVANOVIC, *Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia* ZELJKA NIKITOVIC, ZORAN PETROVIC, *Institute of Physics, University of Belgrade, Serbia* Transport properties of F+ and F- ions in BF_3 in DC fields and at room temperature were calculated by using Monte Carlo simulation technique. Previously cross section sets were obtained by using Nanbu theory for resolving between elastic and reactive collision events and then resolving contribution of exothermic processes from available experimental data. We present transport coefficients for the conditions of low and moderate reduced electric fields E/N

(E-electric field, N-gas density) accounting for non-conservative processes.

CT1 23 The rf breakdown voltage curves-similarity law* MARIJA SAVIC, MARIJA RADMILOVIC-RADJENOVIC, MILOVAN SUVAKOV, ZORAN LJ. PETROVIC, *Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgarde Serbia* Capacitively coupled radio frequency (rf) discharges are attracting an increased attention due to their wide applications in many technological processes such as plasma etching for semiconductor materials, thin film deposition and plasma cleaning. One of the crucial problem in optimizing plasma technological process is determination of the plasma operating conditions which can be obtained from the breakdown voltage. It was shown that the RF breakdown voltage curves obey similarity law: Vrf =f(pd,f · d=const), where p is the gas pressure, d is the interelectrode distance and f is t the operating frequency. We have performed calculations in argon by using Monte Carlo code considering only electrons motion. Simulation conditions were based on the experimental conditions. The obtain results confirm similarity law and satisfactorily agree with the available experimental data.

CT1 24 GLOWS: DC, PULSED, MICROWAVE, OTHERS

CT1 25 Glow Discharge with Confinement of Electrons in an Electrostatic Trap ALEXANDER METEL, *Moscow State University of Technology "STANKIN"* Theory based on the concept of the gas ionization cost W is found to be in a good agreement with experimental study of the glow discharge with electrostatic trap in the gas pressure range 0.001-10 Pa. When the mean ionization length λ of emitted by the cathode electrons exceeds the trap width $a = 4V/S$, where V is the trap volume and S is area of the trap boundary, and their energy relaxation length $\Lambda = (eU_c/W)\lambda$, where U_c is cathode fall of potential, is lower than the trap length $L = 4V/S_o$, where S_o is output aperture of the trap, U_c is independent of the pressure p. In this middle pressure range due to multiplication of fast electrons in the cathode sheath U_c diminishes about 2 times from its maximum $W/e\gamma$, where γ is coefficient of ion-induced electron emission, with the discharge current reduction. At $\Lambda > L$ the cathode fall U_c rises from hundreds to thousands of volts and p tends to the discharge extinction pressure p^{ex}, at which the ionization length λ of electrons with energy equal to the energy of electrons emitted by the cathode in the middle pressure range is equal to L.

CT1 26 Research of the DC discharge of He-Ne gas mixture in hollow core fiber* XINBING WANG, LIAN DUAN, *Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology* Since the first waveguide 0.633 μm He-Ne laser from a 20 cm length of 430 μm glass capillary was reported in 1971, no smaller waveguide gas laser has ever been constructed. Recently as the development of low loss hollow core PBG fiber, it is possible to constract a He-Ne lasers based on hollow-core PBG fibers. For the small diameter of the air hole, it is necessary to do some research to obtain glow discharge in hollow core fibers. In this paper, the experimental research of DC discharge in 200 μm bore diameter hollow core fibers was reported. Stable glow discharge was obained at varioue He-Ne mixtures from 4 Torr to

18 Torr. In order to obtain the plasma parameter of the discharge, the trace gasses of N_2 and H_2 were added to the He-Ne mixtures, the optical emission spectroscopy of the discharge was recorded by a PI 2750 spectroscopy with a CCD camera. The gas temperature (Tg) could be obtained by matching the simulated rovibronic band of the N_2 emission with the observed spectrum in the ultraviolet region. The spectral method was also used to obtained the electron density, which is based on the analysis of the wavelength profile of the 486.13 nm H_β line, and the electron temperature was obtain by Boltzmann plot methods. Experimental results show that it is very difficult to achieve DC discharge in bore diameter less than 50 μm, and a RF discharge method was proposed.

CT1 27 The Child-Langmuir laws and cathode sheath in the N_2O VALERIY LISOVSKIY,* EKATERINA ARTUSHENKO, VLADIMIR YEGORENKOV, *Kharkov National University, Svobody Sq.4, Kharkov 61022, Ukraine* It is established which of the Child-Langmuir collisional laws are most appropriate for describing the cathode sheath in the N_2O. At low pressure $p < 0.3$ Torr the Child-Langmuir law version relating to the constant ion mobility. At $p > 0.75$ Torr one has to employ the law version for which it is assumed that ion mean free path within the cathode sheath is constant. In the intermediate pressure range $0.3 < p < 0.75$ Torr neither of the Child-Langmuir law versions gives a correct description of the cathode sheath in the N_2O. The ratio of the normal current density to the gas pressure squared J/p^2, the normal voltage drop and the cathode sheath thickness are determined. For the stainless steel cathode they equals to $U = 364$ V and $pd = 2.5$ Torr $\cdot$ mm. At large N_2O pressure the above ratio remains constant and it amounts to $J/p^2 = 0.44$ mA/(cm $\cdot$ Torr)^2 for any inter-electrode gap value we studied. On decreasing the N_2O pressure the ratio J/p^2 increases and for narrow gaps between electrodes it may approach several or even several tens mA/(cm $\cdot$ Torr)^2.

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CT1 28 VUV Emission of Microwave Driven Argon Plasma Source* JULIO HENRIQUES, SUSANA ESPINHO, EDGAR FE-LIZARDO, ELENA TATAROVA, FRANCISCO DIAS, CARLOS FERREIRA, *Institute of Plasmas and Nuclear Fusion, Instituto Superior Tecnico, Technical University of Lisbon, Portugal* An experimental and kinetic modeling investigation of a low-pressure (0.1-1.2 mbar), surface wave (2.45 GHz) induced Ar plasma as a source vacuum ultraviolet (VUV) light is presented, using visible and VUV optical spectroscopy. The electron density and the relative VUV emission intensities of excited Ar atoms (at 104.8 nm and 106.6 nm) and ions (at 92.0 nm and 93.2 nm) were determined as a function of the microwave power and pressure. The experimental results were analyzed using a 2D self-consistent theoretical model based on a set of coupled equations including the electron Boltzmann equation, the rate balance equations for the most important electronic excited species and for charged particles, the gas thermal balance equation, and the wave electrodynamics. The principal collisional and radiative processes for neutral Ar($3p^54s$) and Ar($3p^54p$) and ionized Ar($3s3p^6$ $^2S_{1/2}$) levels are accounted for. Model predictions are in good agreement with the experimental measurements.

CT1 29 On electric field magnitude on the cathode surface in the negative corona discharge* A. PETROV, S. SAVINOV, *P.N. Lebedev Physical institute of RAS* N. PESTOVSKII, E. KOROSTYLEV, *Moscow institute of physics and technology* R. AMIROV, I. SAMOYLOV, *Joint institute for high temperatures of RAS* S. BARENGOLTS, *A.M. Prokhorov General physics institute of RAS* Negative corona discharge has been studied in air in the Trichel pulse mode in point-to-plane configuration on graphite cathodes. Electric field magnitude of the positive space charge in the active phase of a Trichel pulse has been estimated on the range of 10^7 V/cm. The discharge flame on the cathode surface is localized in the region with maximum electric field [1]. The wandering of the discharge is self-organized in such way that the electric field magnitude caused by the positive space charge in the region of the discharge flame localization exceeds the field magnitude on the microasperities in some distance from this region. So the proposed estimate of electric field magnitude is based on the results of the topography analysis of the cathode surface and on the results of registration of the discharge wandering over the cathode surface. Microasperities formed due to redeposition of erosion products with field magnification coefficient $10\text{-}10^2$ were found. Finally the occurrence of electric field with magnitude 10^8 V/cm argues in favor of electroexplosive mechanism of cathode erosion in the negative corona discharge.

[1]Loeb, L.B. Electrical Coronas. Their Basic Physical Mechanisms. Berkeley, CA: Univ. California Press, 1965, 694 p.

CT1 30 Axial structure of the dc hollow cathode discharge at different modes VALERIY LISOVSKIY,* ILLIA BOGODIEL-NYI, *Kharkov National University, Svobody Sq.4, Kharkov 61022, Ukraine* This paper reports the axial profiles of the electron temperature, plasma concentration and plasma potential in a dc hollow cathode discharge in nitrogen registered with probe technique. At low pressure (0.05 Torr) the discharge is shown to burn in a high-voltage (electron-beam) mode. Electron temperature does not exceed 1 eV in the total plasma region excluding an abrupt growth in the vicinity of the cathode sheath boundary. A potential barrier is found near the cathode sheath boundary, for the current value of 1 mA the height of this barrier amounts to about 8 V. At gas pressure $p \geqslant 0.15$ Torr two modes are well expressed: glow and hollow ones. At low discharge current a glow regime is observed in which the negative glow from the anode side possesses a wedge-like profile directed into the cathode cavity. At larger discharge current the discharge is burning in the hollow mode in which the cavity is filled with a high concentration plasma approaching $2 \cdot 10^{10}$ cm^{-3} and an electron temperature exceeding 2 eV. A potential well about 3 V deep is observed near the edge of the cathode cavity. On increasing the gas pressure the depth of the potential well in the cathode cavity decreases and it disappears at 0.5 Torr.

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CT1 31 Physics and modeling of ITER glow discharge cleaning* G.J.M. HAGELAAR, *LAPLACE, CNRS and University of Toulouse, France* D. KOGUT, D. DOUAI, *CEA, IRFM;*

Association Euratom-CEA, France R.A. PITTS, *ITER Organization* Glow discharge cleaning (GDC) is a common technique for the conditioning of tokamak vessel walls in order to improve the tokamak plasma performance and reproducibility. The GDC discharge is a dc low-temperature plasma discharge, operated when the tokamak magnetic fields are off, between several anodes inserted into the vessel, and the vessel walls serving as a cathode. The plasma is sustained by fast electrons emitted from the walls by ion impact, accelerated through a thin cathode sheath up to nearly the discharge voltage, and then penetrating very far into the plasma. On the other hand, the electric potential in the plasma bulk, which determines the wall ion flux distribution, seems to be controlled by low-energy bulk electrons. This paper presents a self-consistent 2D model of the GDC discharge with the aim to improve fundamental understanding and predict the wall current density distribution as input to the ITER GDC system design. The model is based on a hybrid approach, combining a fluid model of the plasma bulk with a Monte-Carlo simulation of the fast electrons. Comparisons are shown with experimental results obtained on a small scale test stand.

This work is funded by the IO-CEA/IRFM contract IA #14 ref 42-586 FRW 6-49.

CT1 32 A novel self-excited oscillator as RF amplifier for capacitive discharge at atmospheric pressure XIANGYU XU, YINGQI MA, YI ZHOU, YU WANG, *Academy of Opto-electronics, Chinese Academy of Sciences* ACADEMY OF OPTO-ELECTRONICS, CHINESE ACADEMY OF SCIENCES TEAM   A novel self-excited oscillator was developed for exciting atmospheric pressure plasma via capacitive-discharge way. The oscillator was dominated by a RF transformer combined with a feedback inductor. The frequency range can be tuned from 1 to 15 MHz by changing the values of the resonant capacitor and the feedback inductor. The optimum output power was determined by the capacitive-discharge plasma's volume and the maximum value was about 80 W. By square-wave frequency modulation of the DC supply, the mode of filament discharge or glow discharge was successfully controlled by the oscillator excitation. The developed oscillator can be used for atmospheric pressure plasma for small volume and small power device applications, such as plasma jet, flat capacitor discharge, etc.

CT1 33 Plasma Photonic Crystals for Microwave Manipulation BENJAMIN WANG, MARK CAPPELLI, *Stanford University*   A plasma photonic crystal was constructed for microwave manipulation and the performance of the device was characterized. A linear waveguide and square plasma photonic crystal was constructed from arrays of plasma glow discharge tubes. The transmission spectrums of the devices were measured and characterized. Finite difference time domain (FDTD) simulations of the designed 2D waveguide plasma devices in air were completed. The introduction of point and line defects in the plasma arrays allowed for waveguiding behavior and electromagnetic band gaps to be observed.

CT1 34 Simulations of energy and angular distributions in plasma processing reactors using CFD-ACE+ ANANTH BHOJ, KUNAL JAIN, MUSTAFA MEGAHED, *ESI US R&D Inc*   Several plasma processing reactors employ energetic ion bombardment at the substrate to enable surface reactions such as plasma etching, deposition or sputtering. The knowledge and control of the energy and angular distributions is an important requirement and can be used to suppress or enhance reaction rates. The CFD-ACE+ platform is used for reactor scale modeling of generic inductively coupled and capacitively coupled rf plasma reactors. CFD-ACE+ has a coupled solver approach that includes modules to address in a sequential and iterative manner, fluid flow, heat transfer, the Poisson equation for electric fields, charged species transport equations for species fluxes, surface charge on dielectrics and chemical kinetics in the gas and on all plasma-bounding surfaces. The Monte Carlo transport module of CFD-ACE+ is based on the work of Kushner and co-workers* and tracks pseudo-particles representing actual species based on source functions in the reactor. Model outputs for visualization include species densities and energy and angular distribution functions. Results discussed will include the effect of process variables such as pressure, power and frequency on the energy and angular distributions.

*R. J. Hoekstra and M.J. Kushner, Journal of Applied Physics, **79**, 2275 (1996).

CT1 35 Simulations of DC planar magnetron discharges using CFD-ACE+ ANANTH BHOJ, KUNAL JAIN, MUSTAFA MEGAHED, *ESI US R&D Inc*   Among the various kinds of plasma reactors, DC magnetron discharges are a class of reactors that utilize dc electric fields and strong magnetic fields to confine or otherwise manipulate the discharge properties and consequent details of sputtering to suit processing needs. In this work, the plasma modeling platform, CFD-ACE+, was used to simulate DC discharges in the presence of strong magnetic fields, not accounting for sputtering effects. CFD-ACE+ consists of several coupled physics modules and the partial list of those used here solve for volumetric and surface reactions, heat transfer, electromagnetics and species transport. Anisotropic electron transport in the presence of strong magnetic fields is included in the model. An axisymmetric DC discharge with a grounded anode and powered cathode and static magnetic field (also axisymmetric) was investigated. The effect of magnetization and secondary electron emission on plasma density and sheath thickness are discussed. The variation of species fluxes, energy and angular distributions at the cathode are examined.

CT1 36 MAGNETICALLY-ENHANCED PLASMAS: ECR, HELICON, MAGNETRON, OTHERS

CT1 37 Observation of counter flowing E × B drifts in annuls magnetized plasma column of a d.c magnetron source SHANTANU KARKARI, *Institute for Plasma Research, Bhat, Gandhinagar* SOURABH JAIN, ISHETA MAJUMDAR, *Indian School of Mines, Dhanbad* HASMUKH KABARIYA, CHIRANJEEV SONEJI, DHRUMIL PATEL, *Institute for Plasma Research, Bhat, Gandhinagar*   High density plasma sources based on magnetron devices are widely popular in thin film deposition systems. In this paper we present the characteristic properties of an intense magnetized plasma column produced using a d.c magnetron source. The plasma column extends up to a distance of 50 cm in the presence of uniform magnetic field ranging up to 150 mTesla. The device comprise of a hollow cathode of diameter 5 cm and a differentially pumped constricted hollow anode. Measurement of radial plasma parameters using planar Langmuir probe shows an off-centered density peak exceeding 10^{17} m^{-3} at a distance of 15 cm from the source. The detail analysis of the electron-saturation region of the probe characteristics in the central column shows a double hump structure at approximately 10 Volts above the plasma potential. This feature reveals the presence of an ion beam in the plasma column

which is absent outboard from the axis. In addition energetic electrons having energies greater than 100 eV are also inferred from the probe characteristic. Preliminary assessment regarding the origin of these energetic particles is attributed to the possibility of a virtual anode inside the magnetron device.

CT1 38 Steady-state mode of DC magnetron sputtering of mosaic copper-graphite targets*

ALEXANDER PAL, YURY MANKELEVICH, *MSU SINP, Moscow, RF* VALERY MITIN, *VNIINM, Moscow, RF* TATYANA RAKHIMOVA, ALEXEY RYABINKIN, ALEXANDER SEROV, *MSU SINP, Moscow, RF* Magnetron discharge provides broad possibilities for complex materials engineering, multicomponent coatings deposition in particular. Sputtering of the segmented or mosaic targets could easily create the necessary film composition. However the metal flux from the target can hardly be uniform. That is because removing a material is a ballistic process that considerably depends on many coupled processing parameters. The differences in the sputter yield of the different target segments should lead to non-uniform target erosion and distortion of the stoichiometry of a multi-element target material in the film. We investigated the magnetron sputtering of the mosaic targets containing materials with heavily different sputtering yield, namely copper and carbon. The mosaic targets consisted of copper disks with cylindrical graphite inserts. The relative area of the inserts was varied. It was found, that after transition regime an operational mode with equal erosion rate of metal and graphite elements were established. The ion flow redistribution due to graphitic insets protruding above the copper surface and the graphite sputtering yield increase due to Cu and Ar implantation can explain the effect of sputtering rate equalization for mosaic copper-graphite targets. The same processes should take place at sputtering of mosaic targets with small inserts of any composition.

CT1 39 High current density and low sputtering in cold cathode glow plasmas*

SERGEY ZALUBOVSKY, SVETLANA SELEZNEVA, DAVID SMITH, DARRYL MICHAEL, TIMOTHY SOMMERER, *GE Global Research* We investigate the use of cold cathodes in long-life high-voltage gas switches In such an application the current density should be high (to maximize the device current rating), the gas pressure should be low (to maximize standoff voltage on the left side of Paschen's curve), and cathode sputtering should be minimized (for long device life). We focus here on the rate of cathode sputtering as a function of both cathode materials and plasma conditions. The plasma is magnetized to increase the current density, and operates at an intermediate gas pressure, so we estimate the ion energy distribution at the cathode surface as a function of plasma parameters using both semi-analytic expressions and a particle-in-cell simulation.

CT1 40 Electron transport in closed-drift EXB configurations - Collisional to turbulent transport

JEAN-PIERRE BOEUF, *LAPLACE, CNRS and University of Toulouse* In closed-drift ion sources and Hall thrusters, the presence of a magnetic field perpendicular to the electron current between an emissive cathode and the anode leads to the formation of a large electric field in the plasma, which extracts ions from the source. In typical cylindrical configurations, the external magnetic field is radial and the electric field is axial, and a large electron current, the Hall current, flows in the azimuthal EXB direction (closed-drift). In Hall thruster conditions, it is known that collisions between electrons and neutral atoms cannot explain the observed electron current across the magnetic field. We use a 1D-3V Particle-In-Cell Monte Carlo Collision (PIC-MCC) model to study electron transport in these conditions. Electron and ion trajectories are described in 3D but Poisson's equation is solved in the azimuthal direction only (with periodic boundary conditions) to study the development of instabilities in this direction. Electrons gain energy form the given axial electric field and lose energy through collisions with neutral atoms. Simulations have been performed for different gas densities, plasma densities, and applied E and B fields. We find that instabilities of the azimuthal electric field take place quickly for values of the Hall parameter larger than one. We study the properties of these instabilities, compare them with those predicted by dispersion relations obtained in similar conditions, and analyze the deviation from classical mobility due to these instabilities.

CT1 41 Warm Magnetized Primary and Secondary Electron Vlasov Equilibria*

ROBERT TERRY, *Enig Associates, Inc.* A Vlasov equilibrium is developed for steady state emission into a magnetized gap in coaxial geometry. The outer cathode boundary conditions are those of a perfect conductor that emits a Maxwellian electron flux radially, azimuthally, and axially. The interior anode boundary conditions are those of a perfect conductor with a fixed secondary emission coefficient ($0 < \gamma \leqslant 1$). The anode carries a fixed current and the radial gap is set to a fixed voltage. The angular momentum of emitted secondary electrons around the anode is found to materially change the orbit turning points. When energy conserving solutions are examined it is found that the secondaries axial velocities must remain bounded above by a well defined function of radius, magnetic field, and voltage. A fully nonlinear and self consistent Vlasov-Poisson problem is formulated and solved for the space charge distribution implied by the Vlasov equilibrium. The conditions for magnetic insulation of the secondary electron population are then established.

CT1 42 HIGH PRESSURE DISCHARGES: DIELECTRIC BARRIER DISCHARGES, CORONAS, BREAKDOWN, SPARKS

CT1 43 Ignition mechanism of mercury-free HID lamps for automotive headlamps

TADAO UETSUKI, TAKAO SHIMADA, RYOTA YAMAMOTO, KOTARO SHIMIZU, *Tsuyama National college of Technology* MASAYA SHIDO, YUKIO ONODA, *Koito Manufacturing Co., Ltd.* It is important to decrease the ignition voltage of the mercury-free HID lamp for automotive headlamp in order to make their ballast smaller. We think it is necessary to understand how the discharge starts and grow in the HID lamp burner in order to decrease the ignition voltage. An ultra high speed camera was used for the observations of the discharge, the shutter speed of which is 5n seconds. As the result, we found the discharge grow through three stages. First, a very weak discharge occurs outside the burner. Second, the very weak plasma was formed near the cathode in the burner, and then it grew toward the anode. Finally, a strong discharge like streamer developed from the anode to the cathode. The weak plasma seems to be made by the strong electric field formed by the attached electric charge on the outside of the burner

wall, which was formed by the first weak discharge that occurred outside of the burner. In this study we discuss these observations.

CT1 44 Thomson scattering in high-pressure microwave plasmas for plasma-assisted combustion in automobile engines K. SASAKI, S. SOMA, *Hokkaido University* Y. IKEDA, *Imagineering, Inc.* Nonequilibrium plasmas are preferable in plasma-assisted combustion of automobile engines. We have developed a microwave plasma source, which can work at pressures higher than the pressure of atmosphere, with the intension of applying it to plasma-assisted combustion. In this work, we investigated the electron temperature in the microwave plasma source by laser Thomson scattering. The power supply for the discharge was a semiconductor-based microwave source at 2.45 GHz. We produced pulsed discharges with a duration of 2 ms. The discharge gas in this experiment was helium. We constructed a triple-grating spectrograph with a focal length of 200 mm and three diffractive gratings of 1800 grooves/mm. The light source was the second harmonic of a Nd:YAG laser (532 nm). The spectrum of the scattered laser light was recorded using an ICCD camera working at the photon-counting mode. The electron temperature observed experimentally ranged between 1 and 2.5 eV even when the plasmas were produced at pressures up to 0.3 MP. On the other hand, the gas temperature, which was evaluated from the optical emission spectrum of impurity OH, was lower than 1800 K. Therefore, we have confirmed that a nonequilibrium plasma can be produced in helium at pressures higher than the pressure of atmosphere.

CT1 45 Fluid modelling of the influence of the pulse width in N2-O2 barrier discharges M.M. BECKER, R. BRANDENBURG, H. HÖFT, M. KETTLITZ, D. LOFFHAGEN, *INP Greifswald* Recently, experimental investigations on pulsed driven dielectric barrier discharges in N2-O2 gas mixtures at atmospheric pressure have revealed that the time between subsequent microdischarges influences the discharge characteristics significantly (M. Kettlitz *et al.*, J. Phys. D: Appl. Phys. 45:245201, 2012). Here, the influence of the pulse width in the range from 5 to 50 μs on the particle densities and on the most important reaction kinetic processes in a gas mixture of 0.1 vol% O2 in N2 is analysed. The studies are performed by means of a time-dependent, spatially one-dimensional fluid model taking into account balance equations for the densities of all relevant species and the mean electron energy, Poisson's equation as well as an equation for the surface charge density on the dielectrics. It is shown that in accordance with measurements the model predicts different current-voltage characteristics at the rising and the falling slope of the voltage pulse if the duty cycle is decreased from 50% to 10%. With decreasing pulse width the current maximum at the falling slope also decreases. It is confirmed by the theoretical investigations that for short pulse widths the charge carriers left in the gap play an important role in the reignition dynamics.

CT1 46 Investigating streamer to spark transition in supercritical N2 ARAM H. MARKOSYAN, *Centrum Wiskunde and Informatica, Amsterdam* JIN ZHANG, BERT VAN HEESCH, *Eindhoven University of Technology* UTE EBERT, *Centrum Wiskunde and Informatica, Amsterdam* We simulate the thermal shock and the induced pressure waves caused by electrical breakdown of supercritical nitrogen. We investigate the temperature evolution after breakdown, thus predicting the recovery rate of a plasma switch based on supercritical liquids. The system of fluid equations is used to obtain the spatial and temporal evolution of liquid density, pressure, velocity and energy. We compare simulation and experimental results.

CT1 47 Electromagnetic Simulation of Long-Slotted Waveguide Antenna for Production of Meter-Scale Plasma under Atmospheric Pressure HARUKA SUZUKI, SUGURU NAKANO, *Nagoya Univ.* HITOSHI ITOH, *PLANT, Nagoya Univ., Tokyo Electron Ltd.* MAKOTO SEKINE, MASARU HORI, HIROTAKA TOYODA, *Nagoya Univ., PLANT, Nagoya Univ.* Atmospheric pressure plasmas have been given much attention because of its high cost performance and a variety of possibilities for industrial applications. In various kinds of plasma production techniques such as corona discharge, DBD, pulsed-microwave discharge plasma using slot antenna is attractive due to its ability of high-density plasma production. In this plasma source, however, size of the plasma has been limited up to a few cm in length due to its plasma production mechanism and increase in the plasma size was difficult. In this study, we have successfully increased the length of the slot-antenna plasma source up to 0.7 m by microwave power flow control inside the waveguide. In this plasma source, reflected power that induces standing wave is suppressed and long plasma is produced only by traveling waves inside a long slot. Three-dimensional electromagnetic field simulation is conducted and spatial slight fluctuation of the microwave power, i.e., standing wave, caused by slight reflection power at the end of the long slot antenna is investigated from the simulated result. Relation between spatial fluctuation of the microwave power and the emission intensity will be discussed.

CT1 48 The properties of isolated streamer discharges* JANNIS TEUNISSEN, *Centrum Wiskunde & Informatica* UTE EBERT, *Eindhoven University of Technology* We aim to understand how the basic properties of positive streamer discharges, such as their radius or velocity, depend on the discharge conditions. We systematically explore these properties by doing many simulations under different discharge conditions. The electric field, gas mixture, initial discharge seed and the source of free electrons are varied. The simulations are performed with a fluid model, assuming cylindrical symmetry. To eliminate effects from boundaries, we use a free-space field solver. We compare our results with previous studies and with experimental observations.

CT1 49 Development of a Nitrogen DBD-Plasmajet based on Capillary Discharge Design BERNHARD BOHLENDER, MARCUS IBERLER, JOACHIM JACOBY, *Goethe Universität Frankfurt, IAP* This contribution is about a Nitrogen DBD-Plasmajet at atmospheric pressure. APGD (Atmospheric Pressure Gas Discharges) are used, e.g. for the treatment of surfaces. The experiment presented is such an APGD being developed for medical applications like the sterilization of instruments. The setup is an APGD based Plasmajet constructed as a capillary discharge. The capillary is made of Al2O3 with a thickness of 1.05 mm. Within the capillary is the inner electrode with a borehole of 1.8 mm. The outer diameter of the used capillary is 2.8 mm. The outer electrode is attached on top of the capillary with a variable distance to the inner electrode's ending. The inner electrode is connected to a sinusoidal voltage of up to 10 kV peak-to-peak amplitude at a frequency of 15 kHz. The outer electrode is attached to ground potential. Nitrogen flows through the setup with atmospheric pressure, thus the plasma generated is being pressed out. The next step of the work is to find the resonance frequency of the set up. Simulations of the electrical circuit are performed. In Addition, optical and electrical measurements are planned in order to characterize the plasma

parameters. The further development in the future includes a decrease of the size and a panel constructed of 3 to 4 identical capillary discharges to increase the area of the out coming plasma. Founded by BMBF, Willkomm Stiftung, HIC for FAIR.

CT1 50 Simulations of pulsed gas breakdown between pin-to-pin electrodes* STEPAN ELISEEV, *St Petersburg University, St Petersburg, Russia* VLADIMIR KOLOBOV, *CFD Research Corporation, Huntsville, AL, USA* ANATOLY KUDRYAVTSEV, *St Petersburg University, St Petersburg, Russia* Peculiarities of gas breakdown depend on many factors including gas type, geometry of electrodes, time-dependence of the applied voltage, etc. Effects of these factors on the breakdown dynamics and transitions from Townsend (diffuse) to streamer mechanisms remain not fully understood. This paper is devoted to simulations of Helium breakdown in a pin-to-pin electrode geometry using recently developed Adaptive Mesh Refinement (AMR) capabilities for plasma simulations [V.I. Kolobov & R.R. Arslanbekov, J. Comput. Physics, 231 (2012) 839]. AMR enables high resolution of ionization fronts with sharp gradients of plasma properties developing on fast (electron) scale. We study dynamics of the breakdown phenomena depending on the voltage wave form (rise time), the product of gas pressure and the distance between the electrodes, and geometry of the electrode tip. Starting from a minimal plasma model (immobile ions, drift-diffusion transport of electrons, local ionization, and Poisson solver), we investigate effects of electron thermal diffusion, and background ionization on the development of ionization fronts. Results of simulations are analyzed using previously developed 1D theory of pulsed breakdown and compared with available experimental data for pulsed gas breakdown in similar geometries.

*Supported by a Russian Federal Program and by the US DoE PSC.

CT1 51 Time resolved mass spectrometry of positive ions originated from atmospheric-pressure plasma jet* NENAD SELAKOVIC, NEVENA PUAC, DEJAN MALETIC, GORDANA MALOVIC, ZORAN LJ. PETROVIC, *Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia* We present time-resolved measurements of positive ions originated from the atmospheric pressure plasma jet (APPJ) by using HIDEN HPR60 mass energy analyzer. APPJ was made of Pyrex glass tube with two transparent electrodes (15 mm wide PET foil). The gap between the electrodes was 15 mm, excitation frequency 80 kHz and applied voltage 6-10 $kV_{peak-to-peak}$. Helium flow rate was kept constant at 4 slm. In all measurements the distance between the plasma source and mass spectrometer orifice was 15 mm. Spectrometer detector gating was synchronized with the applied current and voltage signals in order to track in time the signal of detected ions. The internal gate width of HPR60 analyzer was 0.1 μs. We performed time resolved mass spectrometry of most abundant ion species originated from plasma jet: N_2^+(36%), N^+(20%), O_2^+(18.5%), O^+(16.8%), H_2O^+(6.1%), OH^+, NO^+, N_2H^+ and Ar^+ (a few percentage). Results have shown that maximum intensity of nitrogen ions is lagging the maximum of current and voltage signal and maximum intensity for oxygen species is in opposite phase with current-voltage signals.

*Supported by MESTD, RS, III41011 and ON171037.

CT1 52 Thermal ionization instability development in air plasma generated by repetitive ns dielectric barrier discharge ANDREY STARIKOVSKIY, MIKHAEL SHNEIDER, *Princeton University* DANIIL MARINOV, SVETLANA STARIKOVSKAIA, *Ecole Polytechnique* PU TEAM, LPP TEAM

The aim of this paper is to study a transformation of a nanosecond discharge under conditions of high repetitive frequency in a barrier configuration of the electrodes. Nanosecond DBDs at atmospheric pressure are widely used for research in plasma medicine. At atmospheric pressure conditions the discharge develops as a set of microchannels bridging a gap between the electrodes covered with dielectric, the current in each microchannel is restricted by charging of a dielectric surface. With pressure decrease, a discharge becomes more uniform, still it is known that a slight change of a gas mixture composition, f.e. add of a fuel, may lead to significant problems with the uniformity. Estimations were made to analyze the possibility of discharge contruction due to thermal ionization instability development. We used the assumption that there is no convective cooling of the gas in the discharge cell. It was shown that NS discharge in DBD geometry is non-uniform. Initial electrical fields distribution and thermal ionization instability development form the non-uniform energy distribution in the discharge. This non-uniformity can play a key role in kinetic experiments in this type of the discharge.

CT1 53 Spreading of atmospheric pressure plasma jet on a dielectric surface OLIVIER GUAITELLA, EMERIC FOUCHER, ANA SOBOTA, ANTOINE ROUSSEAU, *LPP, Ecole Polytechnique, UPMC, Université Paris Sud-11, CNRS, Palaiseau, France* Atmospheric pressure plasma jets are intensively studied for their potential application in surface treatment as well as biomedical applications. For both applications fields it is essential to understand the dynamics of a plasma jet impinging onto a surface. In this work a plasma jet source is used in a coaxial geometry with a single dielectric barrier discharge configuration powered at 30 kHz. The impact of the plasma jet on various dielectric plates is monitored directly with fast iCCD imaging. The spreading of the discharge over the surface is analyzed by examining the re-ignition of plasma on the other side of the dielectric plate. Properties of the impinging jet are deduced from the limit of re-ignition of the secondary plasma. Special care has been taken to relate the characteristic of the plasma jet source with the spreading of the jet on the surface. The results exhibit a very interesting dynamics of the spreading of the jet which depends on the energy dissipated in the source but also on the dielectric permittivity of the dielectric plate target as well as the whole configuration surrounding the capillary pipes in which the discharge is propagating. These properties are important for controlling any process involving the use of a plasma jet.

CT1 54 The effect of heating mode transition on the electron energy probability function through the variation of driving frequency JUNG YEOL LEE, HYOWON BAE, HAE JUNE LEE, *Pusan National University* JOHN VERBONCOEUR, *Michigan State University* During the last two decades, a number of applications such as a plasma display, surface treatment, and bio-medical devices utilized sub-millimeter atmospheric pressure plasmas. Among them, the dielectric barrier discharge (DBD) is widely used as the simplest device which can sustain abnormal glow discharge with a micro-sized gap length. In this study, a particle-in-cell (PIC) simulation was selected to understand the discharge characteristics of a planar micro DBD with an input frequency from 13.56 MHz to 600 MHz. Along with two different heating modes, the alpha and the gamma mode, the sheath heating by secondary electron emission plays an important role for DBDs. The electron energy probability function (EEPF) shows a bi-Maxwellian profile in gamma mode. On the other hand, Ohmic heating is more dominant for electron temperature in alpha mode, and the increment of input frequency changes the ratio of secondary electron current to the total current

through the relationship between the ion transit time and the driving period. Therefore, the transition mechanism of the EEPF in DBDs is very different from that of low pressure capacitively coupled plasmas. It means that it is possible to control the interactions between plasmas and neutral gas for the generation of preferable radicals by the variation of input frequency through the change of heating mode.

CT1 55 Dynamics of pulsed laser ablation plasmas in high-density CO_2 near the critical point investigated by time-resolved shadowgraph imaging* KEIICHIRO URABE, TORU KATO, SHOHEI HIMENO, SATOSHI KATO, SVEN STAUSS, MO-TOYOSHI BABA, TOHRU SUEMOTO, KAZUO TERASHIMA, *The University of Tokyo* Pulsed laser ablation (PLA) plasmas generated in high-density gases and liquids are promising for the synthesis of nanomaterials. However, the characteristics of such plasmas are still not well understood. In order to improve the understandings of PLA plasmas in high-density fluids including gases, liquids, and supercritical fluids (SCFs), we have investigated the dynamics of PLA plasmas in high-density carbon dioxide (CO_2). We report on experimental results of time-resolved shadowgraph imaging, from the generation of plasma plume to the extinction of cavitation bubbles. Shadowgraph images revealed that the PLA plasma dynamics showed two distinct behaviors. These are divided by gas-liquid coexistence curve and the so-called Widom line, which separates gas-like and liquid-like SCF domains. Furthermore, cavitation bubble observed in liquid CO_2 near the critical point showed peculiar characteristics, the formation of an inner bubble and an outer shell structure, which so far has never been reported. The experiments indicate that thermophysical properties of PLA plasmas can be tuned by controlling solvent temperature and pressure around the critical point, which may be useful for materials processing.

CT1 56 PLASMAS IN LIQUIDS

CT1 57 Breakdown Voltage Scaling in Gas Bubbles Immersed in Liquid Water* SARAH GUCKER, BRADLEY SOMMERS, JOHN FOSTER, *University of Michigan* Radicals produced by the interaction of plasma with liquid water have the capacity to rapidly oxidize organic contaminants. This interaction is currently being investigated as a means to purify water. Direct plasma creation in water typically requires very high voltages to achieve breakdown. Igniting plasma in individual gas bubbles in liquid water on the other hand requires much less voltage. Furthermore, the use of an electrode-less plasma initiation in such bubbles is attractive in that it eliminates electrode erosion thereby circumventing the contamination issue. The breakdown physics of isolated bubbles in liquid water is still poorly understood. In this work, we investigate the relationship between applied voltage for breakdown and the associated pd. This is achieved by locating the breakdown voltage over a range of bubble sizes. This approach allows for the generation of a Paschen-type breakdown curve for isolated bubbles. Such a relationship yields insight into breakdown mechanics and even streamer propagation through water.

CT1 58 Influence of gas and liquid condition on characteristics of self-organized pattern formation observed in atmospheric DC glow discharge* NAOKI SHIRAI, HIROYUKI HIRA-HARA, SATOSHI UCHIDA, FUMIYOSHI TOCHIKUBO, *Tokyo Metropolitan University* Self-organized anode patterns were observed on the surface of a liquid anode when an atmospheric dc glow discharge with helium flow was generated. The pattern formation depends on current, gap length, and helium flow rate. With increasing discharge current or gap length, an anode luminous spot changed to self-organized patterns. Anode pattern formation also depends on liquid conductivity. Although the mechanisms of this pattern formation have not understood completely, we assume that the patterns depend on electronegative gas in the gap and temperature of liquid anode. In this study, we investigate anode pattern formation of the discharge by changing gas condition around the discharge and liquid temperature. When mole fraction rate of oxygen or carbon dioxide is increased, pattern formation is observed. On the other hand, when mole fraction rate of nitrogen is increased, pattern is not observed. If liquid temperature increases, pattern formation changes from dot pattern to stripe pattern.

CT1 59 Global modeling of micro plasma discharge in deionized water SOHAM S. MUJUMDAR, *Department of Mechanical Science and Engineering, University of Illinois at Urbana Champaign* DAVIDE CURRELI, *Center for Plasma-Material Interactions, University of Illinois at Urbana Champaign* SHIV G. KAPOOR, *Department of Mechanical Science and Engineering, University of Illinois at Urbana Champaign* DAVID RUZIC, *Center for Plasma-Material Interactions, University of Illinois at Urbana Champaign* One of the major applications of plasmas in liquids is the micro electro-discharge machining process (μ-EDM) where the material from one of the electrodes is removed by creating repeated pulsed plasma discharges in the inter-electrode gap filled with a dielectric liquid. One of the most commonly used dielectric for the process is deionized water. A model of a single plasma discharge event in deionized water during the μ-EDM process is presented in this paper. The plasma is modeled using a global modeling approach where the plasma is assumed to be spatially uniform, and equations of mass and energy conservation are solved together in conjunction with the expanding plasma bubble dynamics. The model is simulated for different combinations of the applied electric field and the discharge gap distance to obtain complete temporal characterization of the H_2O plasma in terms of the composition of the plasma, temperature of the plasma and the radius of the plasma bubble. The model predicts time-averaged plasma temperature in the range of 12282-29572 K and electron density in the range of $5.12 - 30.22 \times 10^{24}$ m^{-3} for applied electric fields in the range of 10 - 2000 MV/m and discharge gaps in the range of 0.5 - 20 μm.

CT1 60 PLASMA APPLICATIONS

CT1 61 Characterization of Laser Produced Underwater Plasma L. HUWEL, R. HAYDAR, T.J. MORGAN, *Wesleyan University* W.G. GRAHAM, *Queen's University, Belfast* Optical breakdown in water created by 10 ns pulsed Nd:YAG laser

operating at $\lambda = 1064$ nm was studied. Spatial and temporal information was obtained with two intensified CCD cameras while spectral data were recorded using a time-integrating spectrometer. We have studied three water samples with different impurity content (ultra-pure, distilled, and tap water) and followed the plasma evolution over a timespan of a few hundred nanoseconds. Images taken by the two synchronized cameras, systematically delayed relative to each other, show that the "center of emission intensity" in single plasma events moves toward the incoming laser beam. The emission is dominated by a broad, blackbody-like spectral feature with corresponding temperature of ca. 20000 K. Superimposed is a weak hydrogen Balmer-alpha line with a full width at half maximum exceeding 50 nm in some cases. Interpreted as purely Stark broadened, this width corresponds to electron densities well above 10^{19} cm^{-3}.

CT1 62 Development of A Pulse Radio-Frequency Plasma Jet* SHOU-GUO WANG, *Institude of Plasma Physics Chinese Academy of Science* LING-LI ZHAO, JING-HUA YANG, *Institute of Microelectronics Chinese Academy of Sciences* A small pulse plasma jet was driven by new developed radio-frequency (RF) power supply of 6.78 MHz. In contrast to the conventional RF 13.56 MHz atmospheric pressure plasma jet (APPJ), the power supply was highly simplified by eliminating the matching unit of the RF power supply and using a new circuit, moreover, a pulse controller was added to the circuit to produce the pulse discharge. The plasma jet was operated in a capacitively coupled manner and exhibited low power requirement of 5 W at atmospheric pressure using argon as a carrier gas. The pulse plasma plume temperature remained at less than 45 °C for an extended period of operation without using water to cool the electrodes. Optical emission spectrum measured at a wide range of 200–1000 nm indicated various excited species which were helpful in applying the plasma jet for surface sterilization to human skin or other sensitive materials.

*Institude of Plasma Physics, Chinese Academy of Science, Hefei, China.

CT1 63 Pulsed Nanosecond Discharge Development in Liquids with Various Dielectric Permittivity Constants ANDREY STARIKOVSKIY, *Princeton University* PU TEAM The dynamics of pulsed nanosecond discharge development in liquid water, ethanol and hexane were investigated experimentally. High-voltage pulses with durations of 20 and 60 ns and amplitudes of 6-60 kV were used for discharge initiation. It is shown that the dynamics of discharge formation fundamentally differ between liquids with low and high dielectric permittivity coefficients. In water (high permittivity), two phases were observed in the process of the discharge development. The first phase is connected with electrostriction compression of the media near the needle tip and the formation of a rarefaction wave in the surrounding liquid. The second phase (the discharge phase) has a pronounced start delay, which depends on the voltage of the high-voltage electrode. Unlike in water, the first phase is essentially non-existent in liquids with low dielectric permittivity coefficients because of the small electrostriction forces and the low intensity of the rarefaction wave that is formed. The second phase in the process (discharge) begins at significantly higher voltages on the high-voltage electrode, immediately leading to the long branched structure of the streamer-leader flash.

CT1 64 Surface modification of fibers by conducting polymers and their use in composites* HANDE YAVUZ, GREGORY GIRARD, JINBO BAI, *Lab. MSS/MAT, CNRS UMR 8579, Ecole Centrale Paris, 92295 Châtenay Malabry Cedex* LAB. PPSM, CNRS UMR 8531, ENS CACHAN, 94235, CACHAN CEDEX COLLABORATION, ACXYS TECHNOLOGIES FRANCE COLLABORATION Due to the discovery of their incredible functional properties, carbon nanotubes (CNTs) have drawn a great deal of interest from both academic and industrial research teams in the past few years. Since novel materials are to be integrated in structural and functional applications in several fields, inclusion of CNTs as a reinforcement component in polymer matrix composites (PMC) could bring new solutions. However, in order to obtain more advanced CNTs composites, the amount of strong bonding between CNTs and matrix must be realized to ensure the effective stress transfer in a PMC. This research aims to establish an efficient dielectric barrier discharge technique for the surface modification of CNTs grafted carbon fibers (CNTs-CF) with plasma polypyrrole (PPPy) in order to be used in PMC. It is found that response surface methodology can be applicable in modeling to evaluate the effects of important process variables on electrical resistivity of CNTs-CF. From low to high plasma powers, X-ray Photoelectron Spectroscopy studies revealed the loss of α- and β-carbons in pyrrole ring. The higher the plasma power the lower the electrical conductivity and the higher the mechanical properties.

CT1 65 Space – time evolution of low-pressure H2 plasma induced by runaway photoelectrons produced by KrF laser pulse ALEXEY ZOTOVICH, ANDREY VOLYNETS, *Moscow State University, Department of Physics, Moscow, Russia* DMITRY LOPAEV, SERGEY ZYRYANOV, *Nuclear Physics Institute, Moscow State University, Moscow, Russia* KONSTANTIN KOSHELEV, VLADIMIR KRIVTSUN, DMITRY ASTAKHOV, *Institute of Spectroscopy RAS (ISAN), R&D ISAN, Troitsk, Russia* Extreme Ultraviolet Lithography (EUVL) at 13.5 nm is expected to provide the next generation of ULSI. One of hot EUVL problems is contamination of EUV multilayer optics that compels to search methods of in-situ cleaning. The most promising method is to apply H2 plasma generated over the mirror surface by itself EUV radiation. Therefore investigations of EUV-induced plasma are of great interest for developing such cleaning technology. To model evolution of EUV-induced plasma, the study of H2 plasma induced by photoelectrons extracted from a surface by KrF laser pulse has been done. The experiment was carried out by the space-time resolved probe technique while the analysis was made with using plasma model based on 2D PIC MC code as for electrons and for ions. Comparison of experimental and calculated evolution of probe characteristics provided correct applicability of the probe theory and allowed revealing key mechanisms and parameters which control the evolution of photoelectrons-induced plasma.

CT1 66 GREEN PLASMA TECHNOLOGIES: ENVIRONMENTAL AND ENERGY APPLICATIONS

CT1 67 Flame generation and maintenance by non-stationary discharge in mixture of air and natural gas* HENRIQUE DE SOUZA MEDEIROS, *University of Paraiba Valley* JULIO SAGAS, PEDRO LACAVA, *Technological Institute of Aeronautics* Plasma assisted combustion is a promising research field, where the high generation of reactive species by non-equilibrium plasmas is used to modify the combustion kinetics in order to improve the process

either by increasing the production of specific species (like molecular hydrogen) or by decreasing pollutant emission. One typical issue observed in plasma assisted combustion is the increase of inflammability limits, i.e the observation of combustion and flame in situation where it is not observed in conventional combustion. To study the effect of a non-stationary discharge in flame generation and maintenance in a mixture for air and natural gas, the air mass flow rate was fixed in 0.80 g/s and the natural gas flow rate was varied between 0.02 and 0.14 g/s, resulting in a variation of equivalence ratio from 0.4 to 3.0. It is observed a dependence of inflammability limits with the applied power. The analysis by mass spectrometry indicates that the increase of inflammability limits with plasma is due not only applied power, but also to hydrogen production in the discharge. Visual analysis together with high speed camera measurements show a modification in spatial distribution of the flame, probably due to modifications both in flow velocity and flame velocity.

CT1 68 Decolorization of azodyes using the atmospheric pressure plasma jet* SASA LAZOVIC, DEJAN MALETIC, NATASA TOMIC, GORDANA MALOVIC, *Institute of Physics, University of Belgrade, Serbia* UROS CVELBAR, *Jozef Stefan Institute, Ljubljana, Slovenia* ZORANA DOHCEVIC-MITROVIC, ZORAN LJ. PETROVIC, *Institute of Physics, University of Belgrade, Serbia* Atmospheric pressure plasma jet operated in air/argon mixture is tested for decolorization of Bezactiv Orange V-3R dye used in the textile industry. The decolorization efficiency is determined by spectrophotometric measurements at 493.7 nm which corresponds to the breaking of dye N=N bond. The initial concentration of 50 mg/L of dye is reduced 50 times after 120 minutes of treatment by plasma. The results are compared to the efficiency of the suspended TiO_2 powder and activated by an UV lamp (300 W). The radicals responsible for removal of the dye are OH and super-anion radical. It is found that efficiency of the plasma and TiO_2+ UV is quite similar for the treatment times up to 60 min. After that, TiO_2 shows higher decolorization rates (100 times reduction after 90 min). However, when plasma and TiO_2 (but without the UV lamp) are applied together, it is found that there are synergetic effects and that the efficiency is increased. Plasma (less than 2 W) is not expected to produce high amounts of UV light in the atmospheric pressure.

CT1 69 Numerical modeling of CF4 decomposition in low pressure inductively coupled plasma: influence of the O2 concentration MAHSA SETAREH, *University of Tehran University of Antwerp* MORTEZA FARNIA, ALI MAGHARI, *University of Tehran* ANNEMIE BOGAERTS, *University of Antwerp* Perfluorinated compounds (PFCs), which are stable and difficult to decompose, are widely utilized in microelectronic manufacturing. The global warming potential of PFCs is so high in comparison with CO_2 that finding a solution for abating PFC emission is crucial. For this purpose, we performed a numerical simulation of the CF_4 decomposition in an inductively coupled plasma reactor with radio frequency power supply, which is used in semiconductor chamber cleaning process. A zero dimensional modeling code Global_kin developed by Kushner is applied to model the reaction set of CF_4/O_2 in typical plasma reactor conditions, such as 2kW power with frequency of 4 MHz, a pressure of 600 mTorr, and a typical residence time of 0.25 s. The model predicts that the reaction products of

the CF_4 decomposition are mostly COF_2, CO_2 and CO. COF_2 is a toxic compound, but it can be hydrolyzed easily into HF and CO_2 using the scrubber in the reactor. By carefully altering the ratio between CF_4/O_2, the optimum ratio of the CF_4/O_2 gas mixture can be achieved, leading to more than 80% of CF_4 decomposition. The numerical modeling results for CF_4 decomposition are validated based on experimental data from literature.

CT1 70 Plasmas in conducting solutions for treatment of contaminated water COLIN KELSEY, BILL GRAHAM, *Centre for Plasma Physics, Queens University of Belfast* AHMAD MASHAL, DAVID ROONEY, ROBERT GÁMEZ SANS, *School of Chemistry and Chemical Engineering, Queens University of Belfast* A plasma produced in a conducting liquid is compared with more conventional advanced oxidation processes currently used in wastewater treatment such as the Fenton Process. The plasma was produced using a four electrode setup with driving circuitry producing 100 kHz bipolar square waves of approximately 300 V. We compare the effectiveness of the two processes by comparing the reduction in chemical oxygen demand achieved by each. Results indicate that for treatment times of 40 seconds our bench system can achieve a 50% COD reduction across a wide range of input COD concentrations, which is better than the reduction achieved by the single dose Fenton treatment process. Using electrical measurements the efficiency of the plasma process is determined to enable initial estimates of the feasibility of the process for industrial use. Chemical measurements on the plasma system are used to gain insight into the mechanisms underlying the process. These measurements include hydrogen peroxide production rate, which was determined to be 0.5 mg per minute, pH change, which increases with time, but tended to values of 1-3 pH units for characteristic treatment times, and temperature.

CT1 71 Optimization of Industrial Ozone Generation with Pulsed Power JOSE LOPEZ, DANIEL GUERRERO, ALFRED FREILICH, *Seton Hall University* LUCA RAMOINO, *Degremont Technologies - Ozonia* SETON HALL UNIVERSITY TEAM,* DEGREMONT TECHNOLOGIES - OZONIA TEAM† Ozone (O3) is widely used for applications ranging from various industrial chemical synthesis processes to large-scale water treatment. The consequent surge in world-wide demand has brought about the requirement for ozone generation at the rate of several hundreds grams per kilowatt hour (g/kWh). For many years, ozone has been generated by means of dielectric barrier discharges (DBD), where a high-energy electric field between two electrodes separated by a dielectric and gap containing pure oxygen or air produce various microplasmas. The resultant microplasmas provide sufficient energy to dissociate the oxygen molecules while allowing the proper energetics channels for the formation of ozone. This presentation will review the current power schemes used for large-scale ozone generation and explore the use of high-voltage nanosecond pulses with reduced electric fields. The created microplasmas in a high reduced electric field are expected to be more efficient for ozone generation. This is confirmed with the current results of this work which observed that the efficiency of ozone generation increases by over eight time when the rise time and pulse duration are shortened.

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CT1 72 Plasma Acid Formation from the Interaction of a Gliding Arc Plasmatron and Water RYAN ROBINSON, *A.J. Drexel Plasma Institute, Mechanical Engineering & Mechanics, Drexel*

University ALEXANDER GUTSOL, *Chevron Energy Technology* ALEXANDER RABINOVICH, ALEXANDER FRIDMAN, *A.J. Drexel Plasma Institute, Mechanical Engineering & Mechanics, Drexel University* Recently there has been an increased interest in hydrogen production and the bio-medical applications from plasma treated water. Research shows that the interaction of non-thermal plasma discharges and water produces an acidic solution. Hydrogen peroxides and nitrates are commonly produced from the interaction depending on the gaseous environment of the plasma. This study investigates the production of a "plasma acid" from a water spray through a thermal discharge, provided by a DC gliding arc plasmatron (GAP). This method allows for a continuous processing of water rather than the batch processing of other methods that rely on surface interaction with plasma on a volume of water. Air, oxygen, and nitrogen were used as the carrier gas of the water spray and the tangentially fed gas in the discharge region. The production of nitric acid and peroxide was specifically monitored using methods from pH metering, spectrophotometry, and specialized test strips. From air and nitrogen environments there was a small production of peroxide, and larger concentrations of nitric acid. Oxygen environments produced much larger concentration of peroxide, while marginal amounts of nitric acid. In all of the environments, the absorption spectrums showed the presence of other compounds.

CT1 73 Sputtering deposition of ZnGaInON with tunable bandgap for photovoltaics RYOTA SHIMIZU, KOICHI MATSUSHIMA, DAISUKE YAMASHITA, GIICHIRO UCHIDA, HYUNWOONG SEO, KAZUNORI KOGA, MASAHARU SHIRATANI, NAHO ITAGAKI, *Kyusyu University* A material having tunable bandgap is required for significant advance in third generation photovoltaics. Here we propose a novel oxynitride semiconductor ZnGaInON(ZGION), that is a mixed crystal of ZnO, GaN, and InN, and has wurtzite crystal structure. [1] It is fabricated by RF magnetron sputtering. The fascinating feature of ZGION is that the bandgap and the carrier density are controlled by changing the chemical composition ratio. The bandgap has been tuned in a wide range from 1.8 eV to 2.7 eV by controlling [In]/([Zn]+[Ga]+[In]), being ascribed to the narrow bandgap of InN. While the electron carrier density has been reduced from 1.34×10^{21} cm^{-3} to 7.61×10^{20} cm^{-3} by increasing [Ga]/([Zn]+[Ga]+[In]), suggesting that Ga ions play important roles in suppression of carrier generation via anion vacancy formation. These results indicate that ZGION is a potential material for photovoltaics.

[1]N. Itagaki, *et al.*, "Oxynitride semiconductor," U.S. Patent No. 8274078 (2012).

CT1 74 PLASMA PROPULSION AND AERODYNAMICS

CT1 75 The PEGASES gridded ion-ion thruster physics, performance and predictions* ANE AANESLAND, DMYTRO RAFALSKYI, JEROME BREDIN, PASCALINE GRONDEIN, NOUREDDINE OUDINI, PASCAL CHABERT, *LPP, CNRS-Ecole Polytechnique* The PEGASES (Plasma propulsion with Electronegative gases) thruster is a gridded ion thruster that accelerates alternately positively and negatively charged ions to provide thrust. Over the last years various prototypes have been tested, adequate diagnostics have been developed and analytical models and simulations are made to better understand and control the physics involved. The plasma density in the region of the ion-ion plasma predicts that the performance of the PEGASES thruster can be comparable to

existing thrusters on the market. We have recently provided the first experimental proof-of-concept, accelerating alternately positive and negative ions from an ion-ion plasma within a 10 kHz cycle. Here we present the state of the art in the PEGASES development and discuss the various physics involved and its possible future in space.

CT1 76 Pulsed plasma thruster by applied a high current hollow cathode discharge MASAYUKI WATANABE, *Nihon University* N. NOGERA TEAM, T. KAMADA TEAM The pulsed plasma thruster applied by a high current hollow cathode discharge has been investigated. In this research, the pseudo-spark discharge (PSD), which is a one of a pulsed high current hollow cathode discharge, is applied to the plasma thruster. In PSD, the opposite surfaces of the anode and cathode have a small circular hole and the cathode has a cylindrical cavity behind the circular hole. To generate the high speed plasma flow, the diameter of the anode hole is enlarged as compared with that of the cathode hole. As a result, the plasma is accelerated by a combination of an electro-magnetic force and a thermo-dynamic force inside a cathode cavity. For the improvement of the plasma jet characteristic, the magnetic field is also applied to the plasma jet. To magnetize the plasma jet, the external magnetic field is directly induced nearby the electrode holes. Consequently, the plasma jet is accelerated with the self-azimuthal magnetic field. With the magnetic field, the temperature and the density of the plasma jet were around 5 eV and in the order of 10^{19} m^{-3}. The density increased several times as compared with that without the magnetic field.

CT1 77 Analysis of the potential oscillation in Hall thrusters with a two-dimensional particle-in-cell simulation parallelized with graphic processing units* MIN YOUNG HUR, HO-JUN LEE, HAE JUNE LEE, *Pusan National University* WON HO CHOE, *KAIST* JONG HO SEON, *Kyung Hee University* Oscillations of the plasma potential have been observed in many Hall thruster experiments. It was estimated that the oscillations are triggered by the interaction between the plasma and the dielectric materials such as secondary electron emission, but detailed mechanism has not been proven. In this paper, the effects of the interaction between the plasma and dielectric material are simulated with a two-dimensional particle-in-cell (PIC) code for the acceleration channel of the hall thruster. Especially, the simulation code is parallelized using graphic processing units (GPUs). To analyze the effect, the simulation is confirmed to change following two parameters, magnetic flux density and secondary electron emission coefficient (SEEC). The particle trajectory is presented with the variation of the SEEC and magnetic flux density as well as its curvature.

CT1 78 Simulation of electrospray cone-jet mode for electric propulsion applications MANISH JUGROOT, MARTIN FORGET, *Royal Military College of Canada* Understanding the space and time-dependant dynamics of the initiation of electrosprays is highly interesting especially for highly conductive fluids. A multi-component model, coupling fluid dynamics, charged species

dynamics and electric field is applied to flows in capillaries and externally-wetted needles. The simulations describe the charged fluid interface with emphasis on cone-jet transition under the effect of an electric field. The time evolution capture of the interface highlights the close interaction among space charge, coulombic forces and the surface tension in the small scale flows. Droplet, cone-jet and ion modes will be discussed with potential applications to colloid electric spacecraft propulsion.

CT1 79 Efficiency of plasma density control with dc discharge and magnetic field for different surface types in low pressure hypersonic flow IRINA SCHWEIGERT, *Institute of Theoretical and Applied Mechanics* Recently the problem of communication blackout during reentrant flight still remains unsolved. The spacecrafts enter the upper atmospheric layers with a hypersonic speed and the shock heated air around them becomes weakly ionized. The gas ionization behind the shock front is associative in nature and occurs through chemical reactions between fragments of molecules [1]. The formation of a plasma layer near the surfaces of spacecraft causes serious problems related to the blocking of communication channels with the Earth and other spacecrafts. A promising way of restoring the radio communications is the application of electrical and magnetic fields for controlling the plasma layer parameters [2]. Nevertheless the flux of electrons and ions on the surface charges it that essentially decrease the effect of electro-magnetic control of local plasma density. In Ref. [3] it is shown that there is the way to remove the surface charge using the lateral diode string structures. Based on two dimensional kinetic Particle in cell Monte Carlo collision simulations, we study the possibility of local control the plasma layer parameters near a flat surface of two different types. The gas velocity distribution is set with a model profile. We apply DC voltage up to 4 kV and magnetic field B up to 200 G.

[1] I.D. Boyd (2007). Phys. Fluids 19, 096102_1.
[2] M. Keidar, M. Kim, I. D. Boyd (2008). J. Spacecr. Rockets 45, 445.
[3] A. Starikovskiy, R. Miles, AIAA Meeting (Dallas, USA, January 2013) paper N2013-0754.

CT1 80 Dielectric barrier discharge control and thrust enhancement by diode surface ANDREY STARIKOVSKIY, MARTIQUA POST, NICKOLAS TKACH, RICHARD MILES, *Princeton University* PU TEAM The problem of the charge removal is very simple: we need a surface which will conduct the current in one direction and will have high resistance in another to avoid the leakage during the forward discharge development. Lateral diode string structures were designed and successfully manufactured on a 3-inch 4H-SiC semi-insulating wafer. The experiments with direct thrust measurements at low pressure conditions were performed as well as experiments of jet formation at pressure P = 1 atm. It was shown that the plasma conductivity is limiting the charge transfer through the surface. The minimal pulse width value could be estimated as a plasma recombination time. The surface becomes effective suppressor for the reverse breakdown when the conductivity of plasma layer is small enough with compare to the surface conductivity. It means that the reverse breakdown with nanosecond-range delay removes efficiently all surface charges. Effective flow acceleration using diode surface is possible with long pulses with allow full plasma recombination between leading and trailing pulse fronts.

CT1 81 Time-Resolved Laser-Induced Fluorescence Measurements of the Ion Velocity Distribution in the H6 Hall Thruster Plume CHRISTOPHER DUROT, ALEC GALLIMORE, *University of Michigan* We developed a technique to measure time-resolved laser-induced fluorescence signals in plasma sources that have a relatively constant spectrum of oscillations in steady-state operation but are not periodically pulsed, such as Hall thrusters. We present the first results using the new technique to capture oscillations in a Hall Thruster. The ion velocity distribution function in the plume of the H6 Hall thruster is interrogated during breathing mode oscillations. The breathing mode is characterized by an oscillating depletion and replenishment of neutrals at a frequency of about 10-25 kHz. We use laser modulation on the order of megahertz, well above the time scale of interest (about 0.1 ms). Band-pass filtering and phase-sensitive detection (with a time constant on the order of microseconds) raise the signal-to-noise ratio and demodulate the signal while preserving time-resolved information. Following phase-sensitive detection, we average over transfer functions to finish recovering the signal. This technique has advantages such as a shorter dwell time than other techniques and the lack of a need for triggering for averaging in the time domain.

CT1 82 Successful experiments on an external MHD Accelerator: wall confinement of the plasma, annihilation of the electrothermal instability by magnetic gradient inversion, creation of a stable spiral current pattern JEAN-PIERRE PETIT,* JEAN-CHRISTOPHE DORE,† *Lambda Laboratory France* MHD propulsion has been extensively studied since the fifties. To shift from propulsion to an MHD Aerodyne, one only needs to accelerate the air externally, along its outer skin, using Lorentz forces. We present a set of successful experiments, obtained around a model, placed in low density air. We successfully dealt with various problems: wall confinement of two-temperature plasma obtained by inversion of the magnetic pressure gradient, annihilation of the Velikhov electrothermal instability by magnetic confinement of the streamers, establishment of a stable spiral distribution of the current, obtained by an original method. Another direction of research is devoted to the study of an MHD-controlled inlet which, coupled with a turbofan engine and implying an MHD-bypass system, would extend the flight domain to hypersonic conditions.

*Research manager
†Technical manager

CT1 83 Airflows Induced by Asymmetric Bipolar Voltage Pulses in Dielectric Barrier Discharge Plasma Actuator JUNYA SUZUKI, MASANORI DEGUCHI, YOSHINORI TAKAO, KOJI ERIGUCHI, KOUICHI ONO, *Department of Aeronautics and Astronautics, Kyoto University* Dielectric barrier discharge (DBD) plasma actuators have recently been intensively studied for the flow control over airfoils and turbine blades in the fields of aerospace and aeromechanics. The unidirectional gas flow (main flow) is assumed to be induced by the electrohydrodynamic (EHD) body force, where the ambient gas flows are also induced, depending on operating parameters of the discharge such as voltage waveform and amplitude, electrode size and configuration, and dielectric thickness and permittivity. This paper presents experimental studies of airflows in DBD plasma actuators, induced by employing asymmetric bipolar voltage pulses. Schlieren and ICCD imaging exhibited that a variety of flows such as a reverse directional flow, a vortex flow, and a combination of them occur at the opposite side of the main flow, which correlates with the dynamic behavior of DBD plasmas being established.

CT1 84 Initial Experiments of a New Permanent Magnet Helicon Thruster J.P. SHEEHAN, BENJAMIN LONGMIER, *University of Michigan* A new design for a permanent magnet helicon thruster is presented. Its small plasma volume ($\sim$10 cm^{-3}) and low power requirements ($<$100 W) make it ideal for propelling

nanosatellites (<10 kg). The magnetic field reached a maximum of 500 G in the throat of a converging-diverging nozzle and decreased to 0.5 G, the strength of earth's magnetic field, within 50 cm allowing the entire exhaust plume to develop in the vacuum chamber without being affected by the chamber walls. Low gas flow rates (~4 sccm) and high pumping speeds (~10,000 l/s) were used to more closely approximate the conditions of space. A parametric study of the thruster operational parameters was performed to determine its capabilities as both a thruster and as a plasma source for magnetic nozzle experiments. The plasma density, electron temperature, and plasma potential were measured in the plume to characterize the ion acceleration mechanism.

CT1 85 Fluid simulation of a xenon microwave plasma cathode: focus on electron current avalaible and its extraction LAURENT LIARD, YU ZHU, GERJAN HAGELAAR, JEAN-PIERRE BOEUF, *Laplace, CNRS and University of Toulouse, France* Electron sources are a major part of electric propulsion systems, for neutralization of ion beams. Recently, different plasma sources have been investigated as possible alternative cathodes. We presented here a 2D fluid simulation of resonant cavity microwave plasma which has shown promising results [1]. The resonant part of the cylindrical cavity eases the plasma breakdown, and the plasma is then sustained by the microwave through a dielectric. The fluid code has been extensively described in [2]. Results show typical working conditions, and stress the maximum electron current that could be extracted from this kind of discharge, given an absorbed power. Results on the extraction aperture dimensions, and its effect on the actual current obtained are also commented.

[1] K. D. Diamant, IEEE Trans. On Plasma Sci. 37.8, p. 1558 (2009).
[2] Hagelaar, G. J. M., Makasheva, K., Garrigues, L. and Boeuf, J.-P. J. Phys. D: Appl. Phys. 42, 194019 (2009).

CT1 86 GAS PHASE PLASMA CHEMISTRY

CT1 87 Positive & negative streamers in uniform dielectric barrier discharge in atmospheric air CHONG LIU, *A. J. Drexel Plasma Institute. Electrical and Computer Engineering Department, Drexel University* ALEXANDER FRIDMAN, *A. J. Drexel Plasma Institute. Mechanical Engineering and Mechanics Department, Drexel University* DANIL DOBRYNIN, *A. J. Drexel Plasma Institute* One of the most promising and exciting applications of atmospheric air plasmas is medicine. Nanosecond-pulsed Dielectric Barrier Discharge is uniquely suited because, on the one hand, it can be applied directly to the biological target delivering all active species that non-equilibrium plasma can produce, and it produces highly uniform plasma independently of the features of the biological target which permits effective characterization and control of the plasma. Currently, there is no adequate model of the uniform dielectric barrier discharge development in atmospheric air. Here we show that DBD uniformity strongly depends on applied electric field in the discharge gap. We show that the discharge uniformity may be achieved in the case when : 1) strong over voltage (provided by fast rise times), when positive streamers are formed, and 2) short pulse duration that prevents discharge overheating due to rising conductivity which leads to formation of filaments. In the case of strong over voltage on the discharge gap, there is transition from filamentary to uniform DBD mode which may be fundamentally explained by transition from positive to negative streamers.

CT1 88 Ion and atomic species produced in large scale oxygen plasma used for treatments sensitive materials* KOSTA SPASIC, NIKOLA SKORO, NEVENA PUAC, GORDANA MALOVIC, ZORAN LJ. PETROVIC, *Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia* Asymmetric CCP plasma system operating at 13.56 MHz was successfully used for treatments of textile, seeds and polymers. Central electrode (aluminium rod) was powered electrode while the cylindrical wall of the chamber was grounded electrode. We have used mass spectrometry for detections of ions and neutrals in order to get better insight in plasma chemistry involved in surface reactions on treated samples. Besides of ions, one of the important species for surface modifications is atomic oxygen. Actinometry was used as an additional diagnostic tool to determine the extent of atomic oxygen produced in plasma. Measurements were made in several different mixtures of oxygen with addition of several percent of argon. The range of pressures investigated was 150 to 450 mTorr for powers from 100 to 500 W. Measured atomic oxygen density has a steady rise with power (10^{19}-10^{20} m^{-3}). Apart from atomic oxygen species we have detected mass spectra of positive and negative ions. Most abundant ion was O_2^+ while the amounts of O^+ and O^- were smaller by the order of magnitude compared to O_2^+.

CT1 89 Ignition in Ethanol-Containing Mixtures after Nanosecond Discharge ILYA KOSAREV, ALEKSANDR PAKHOMOV, SVETLANA KINDYSHEVA, NIKOLAY ALEKSANDROV, *Moscow Institute of Physics and Technology* ANDREY STARIKOVSKIY, *Princeton University* MIPT TEAM, PU TEAM We study experimentally and numerically kinetics of ethanol ignition after a high-voltage nanosecond discharge. Active particles are produced in a high–voltage nanosecond discharge to favor the ignition of C_2H_5OH-containing mixtures at elevated gas temperatures. We consider stoichiometric ($\varphi = 1$) and lean ($\varphi = 0.5$) C_2H_5OH:O_2 mixtures (10%) diluted with Ar (90%). The gas temperature behind a reflected shock wave ranges from 1100 to 2000 K and the corresponding pressure ranges from 0.2 to 1 atm; these parameters are obtained from measured shock wave velocity. The ignition delay time is measured behind a reflected shock wave with and without the discharge using detection of CH radiation. Generation of the discharge plasma is shown to lead to an order of magnitude decrease in ignition delay time. It is shown that the observed effect of nonequilibrium discharge plasma on ethanol ignition is induced by chain reaction acceleration due to active species generation in the discharge rather than due to fast gas heating. The calculated ignition delay times are compared with the experimental data.

CT1 90 Vapor trapping of evaporated liquids during injection into low pressure plasma* JOHN POULOSE, CAROLINE LIU, *The University of Texas at Dallas* DAISUKE OGAWA, *Chubu University* MATTHEW GOECKNER, LAWRENCE OVERZET, *The University of Texas at Dallas* Liquid injection into low pressure plasma creates a transient change in the gas pressure and plasma properties. Controlling the pressure transient created by evaporation of injected liquids can help reduce unwanted changes in the plasma parameters. We are using an orifice downstream of the liquid injection point to separate the liquid droplets and the evaporated gas from those droplets. Modifying the orifice area to allow droplets to pass through but substantially reduce the conductance of vapor

is being tested. The upper chamber, between the injector and main chamber, is utilized to remove the vapor which initially evaporates off the injected droplets through a rough pump. Additionally, controlling the direction of the droplet injection will assist in targeting the liquid directly into the plasma. To this end, a bellows and injector holder/positioner has been attached to a flange providing approximately fifteen degrees of polar rotation. This is will allow the liquid to reach the plasma, with a reduced pressure transient so that the plasma parameters are maintained. In this poster, we will describe the background of the problem, experimental setup, and results.

CT1 91 Syngas production from tar reforming by microwave plasma jet at atmospheric pressure: power supplied influence* HENRIQUE DE SOUZA MEDEIROS, LUCAS S. JUSTINIANO, MARCELO P. GOMES, ARGEMIRO SOARES DA SILVA SOBRINHO, GILBERTO PETRACONI FILHO, *Technological Institute of Aeronautics* Now a day, scientific community is searching for new fuels able to replace fossil fuels with economic and environment gains and biofuel play a relevant rule, mainly for the transport sector. A major process to obtaining such type of renewable resource is biomass gasification. This process has as product a gas mixture containing CO, CH4, and H2 which is named synthesis gas (syngas). However, an undesirable high molecular organic species denominated tar are also produced in this process which must be removed. In this work, results of syngas production via tar reforming in the atmospheric pressure microwave discharge having as parameter the power supply. Argon, (argon + ethanol), and (argon + tar solution) plasma jet were produced by different values of power supplied (from 0.5 KW to 1.5 KW). The plasma compounds were investigated by optical spectroscopy to each power and gas composition. The main species observed in the spectrum are Ar, CN, OII, OIV, OH, H2, H(beta), CO2, CO, and SIII. This last one came from tar. The best value of the power applied to syngas production from tar reforming was verified between 1.0 KW and 1.2 KW.

SESSION DT1: BASIC PHENOMENA IN LOW TEMPERATURE PLASMA PHYSICS
Tuesday Morning, 1 October 2013; Room: Ballroom I at 10:00; Ralf Peter Brinkmann, Ruhr-University Bochum, presiding

Invited Papers

10:00
DT1 1 Efficient production of Ps and progress towards high densities of Ps*
ADRIC JONES,[†] *University of California, Riverside*

In the last two decades, the development of techniques to store and manipulate large numbers of positrons[‡] has made it possible to study many interesting related phenomena.[§,∥,#] As the number of trapped positrons increases, new experiments are made possible. Recently Cassidy *et al.*[**] have demonstrated that positronium (Ps) is emitted from clean p- and n-type Si surfaces, with very high efficiency. The discovery of an efficient mechanism for producing Ps (as much as $\sim 70\%$ of the incident positrons are converted to Ps at high sample temperatures) paves the way for studies with high densities of Ps. Here I will discuss recent efforts to better characterize the Ps emitted from both p- and n-type Si surfaces, and describe other experiments that are either planned or have been conducted with such Ps beams.

Contributed Papers

10:30
DT1 2 Enhanced ion particle flux and momentum outward of a plasma ball* GENNADY MAKRINICH, AMNON FRUCHTMAN, *H.I.T. - Holon Institute of Technology* A plasma ball has been produced near the anode in a configuration that, when magnetized, operates as a radial plasma source (RPS) [1]. Plasma balls have been studied recently in different configurations [2]. We find that the plasma particle flux outward of the plasma ball is larger than that expected by the Langmuir relation in double layers [3]. The frequency of oscillations of a pendulum is larger than due to gravity only, reflecting the force by the plasma ball. The force by the plasma ball is larger than expected by the model [3]. We address these two questions: the increased ion flux and the increased force relative to the model [3]. We suggest that the Langmuir relation underestimates the ratio of ion to electron flux. We also suggest that the ions gain most of the momentum in the quasi-neutral plasma rather than in the double layer; the impulse enhancement is suggested to result from ion-neutral collisions in the plasma.

[1]G. Makrinich and A. Fruchtman, Phys. Plasmas **16**, 043507 (2009); Appl. Phys. Lett. **95**, 181504 (2009); Phys. Plasmas **20**, 043509 (2013).
[2]R. L. Stenzel, C. Ionita, and R. Schrittwieser, J. Appl. Phys. **109**, 113305 (2011).
[3]I. Langmuir, Phys. Rev. **33**, 954 (1929); B. Song, N. DAngelo, R. L. Merlino, J. Phys D: Appl. Phys. **24**, 1789 (1991).

10:45
DT1 3 Experimental study of charged particle transport in a magnetized low-temperature plasma* R. BAUDE, F. GABORIAU, G.J.M. HAGELAAR, *LAPLACE, University de Toulouse, France* Magnetized low-temperature plasmas are widely used in different types of applications: materials processing, space propulsion, or neutral beam injection. However, the role of the magnetic field in these plasmas is not fully understood, in particular when the plasma chamber has no cylindrical symmetry. The magnetic drift is then bounded by the walls and can play an important role in the plasma transport. In this work, an experimental set up has been developed to study electron transport across a magnetic field barrier and obtain experimental data for the validation of magnetized plasma models, in conditions similar to those of negative ion sources for neutral beam injection. In order to experimentally characterize the electron transport, the local ion and electron current densities at the walls are measured. The diagnostic used is a wall current probe similar to a segmented planar probe designed and developed to spatially and temporally measure the ion and electron current density. The experimental current density profiles are compared with current density profiles calculated with a 2D fluid model.

11:00
DT1 4 Cross-field diffusion in low-temperature plasma discharges of finite length DAVIDE CURRELI, *University of Illinois at Urbana Champaign* The long-standing problem of plasma diffusion across the magnetic field is here critically reviewed, focusing on low-temperature linear devices of finite length having the magnetic field aligned mainly along one axis of symmetry. After a review of the past six decades of works on both the experimental measurements and the theoretical interpretations, we compare and discuss the results obtained from different approaches. Macroscopic fluid-based models can give a first order description of the quasi-neutral region of the plasma. Microscopic calculations of the kinetic motion of plasma particles using three dimensional Particle-in-Cells evidence the big relevance of electrons kinetics, not revealed when electrons are simply approximated as Boltzmann-like. We highlight the relevance of including into the description also the non-neutral region of the sheath boundary, where quasi-neutrality is broken and ions become supersonic, and the wall, whose electrical short-circuiting interaction with the plasma can't be neglected.

11:15
DT1 5 Void dynamics in low-pressure acetylene RF plasmas* FERDINANDUS MARTINUS JOZEF HENRICUS VAN DE WETERING, SANDER NIJDAM, JOB BECKERS, GERARDUS MARIA WILHELMUS KROESEN, *Eindhoven University of Technology, Department of Applied Physics, P.O. Box 513, 5600 MB Eindhoven, the Netherlands* In low-pressure acetylene plasmas, dust particles spontaneously form under certain conditions. This process occurs in a matter of seconds to minutes after igniting the plasma and results in a cloud of particulates up to micrometer sizes levitated in the plasma. We studied a capacitively coupled radiofrequency plasma under normal gravity conditions and constant flow of feed gas (argon and acetylene). After the dust cloud has been formed, an ellipsoid-shaped dust-free zone – called a void – develops and grows as a function of time. Concurrently, the dust particles grow in size. Peculiar dynamics of the void have been observed, where during its expansions it suddenly stops growing and even shrinks, to shortly thereafter resume its expansion. We infer this is induced by coagulation of a new batch of dust particles inside the void. The whole dust growth and void expansion/contraction is periodical and highly reproducible. Several techniques are used to gain information about the plasma dynamics. Microwave cavity resonance spectroscopy is used to determine the global electron density. Scattering of a vertical laser sheet is used to visualize the dust particle density. The electrical characteristics of the plasma are determined using a commercially available plasma impedance monitor.

11:30
DT1 6 Acoustic nonlinear periodic waves in pair-ion plasmas SHAHZAD MAHMOOD, *PINSTECH, Islamabad* TAMAZ KALADZE, *Govt. College Lahore* HAFEEZ UR-REHMAN, *PINSTECH, Islamabad* Electrostatic acoustic nonlinear periodic (cnoidal) waves and solitons are investigated in unmagnetized pair-ion plasmas consisting of same mass and oppositely charged ion species with different temperatures. Using reductive perturbation method and appropriate boundary conditions, the Korteweg-de Vries (KdV) equation is derived. The analytical solutions of both cnoidal wave and soliton solutions are discussed in detail. The phase plane plots of cnoidal and soliton structures are shown. It is found that both compressive and rarefactive cnoidal wave and soliton structures are formed depending on the temperature ratio of positive and negative ions in pair-ion plasmas. In the special case, it is revealed that the amplitude of soliton may become larger than it is allowed by the nonlinear stationary wave theory which is equal to the quantum tunneling by particle through a potential barrier effect. The serious flaws in the earlier published results by Yadav *et al.*, [PRE 52, 3045 (1995)] and Chawla and Misra [Phys. Plasmas 17, 102315 (2010)] of studying ion acoustic nonlinear periodic waves are also pointed out.

11:45
DT1 7 Dynamic contraction of the positive column of a self-sustained glow discharge in molecular gas flow MIKHAIL MOKROV, *Institute for Problems in Mechanics, RAS, Moscow 119526, Russia* MIKHAIL SHNEIDER, *Princeton University, Princeton, New Jersey 08544, USA* GENNADY MILIKH, *University of Maryland, College Park, Maryland 20742, USA* We study dynamic contraction of a quasineutral positive column of a self-sustained glow discharge in nitrogen and air in a rectangular duct with the convection cooling. A set of time-dependent two-dimensional equations for the nonequilibrium weakly-ionized plasma is formulated, and then solved numerically. Transition from diffusive state to contracted one is analyzed. It is shown that in nitrogen the contraction occurs in the so-called "hard" or hysteresis mode while in air the character of the transition depends on pressure. Under relatively high pressure, hysteresis does not occur and the transition takes place in so called "soft" mode. When the pressure reduces and thus the role played by electron attachment diminishes, the transition in air occurs in the hysteresis mode. In such a case the inhomogeneous contraction can occur, when a high density plasma channel starting from the initial perturbation near one electrode propagates to the opposite electrode. The discharge evolution of such kind is computed for a case of self-sustained glow discharge in nitrogen. The results are in agreement with experiment.

SESSION DT2: HIGH PRESSURE DISCHARGES:
DIELECTRIC BARRIER DISCHARGES, CORONAS,
BREAKDOWN, SPARKS I
Tuesday Morning, 1 October 2013
Room: Ballroom II at 10:00
Brian Sands, UES Inc., presiding

Contributed Papers

10:00

DT2 1 Effect of electrodes photoemission on breakdown voltage of Townsend plasma discharges in helium and argon, gaseous and supercritical DEANNA A. LACOSTE, *EM2C Laboratory CNRS / Ecole Centrale Paris* HITOSHI MUNEOKA, *The University of Tokyo* THIBAULT F. GUIBERTI, *EM2C Laboratory CNRS / Ecole Centrale Paris* KEIICHIRO URABE, SVEN STAUSS, KAZUO TERASHIMA, *The University of Tokyo* We report on the effect of light irradiation of tungsten electrode surface on the breakdown voltage in helium and argon for densities up to 23 mol/L. The electric discharges were generated in a pin-to-plane electrode geometry, separated by a gap distance of 5 μm, the pin electrode being the cathode. The applied voltage was generated by a DC power supply with a current limitation of a few tens of nano-amperes. Two light sources with wavelengths of 365 and 635 nm respectively, were used to irradiate the electrodes and the plasma zone and we studied the influence of the pressure, the temperature, and the light flux on the breakdown voltage. With a light flux of less than a few watts per square meter and by varying the pressure near the critical temperature, the breakdown behavior of both helium and argon follows a Paschen curve. In low temperature helium (down to 5.2 K), a strong effect of the light on the breakdown voltage has been found. In contrast, no significant effect has been observed for the breakdown behavior in argon as well as in helium at temperatures higher than 250 K. Based on the results, we propose a phenomenological interpretation of the influence of photoemission on the breakdown mechanism.

10:15

DT2 2 Atmospheric Pressure Non-Thermal Air Plasma Jet* ABDEL-ALEAM MOHAMED, AHMED AL-MASHRAQI, MOHAMED BENGHANEM, *Department of Physics, Faculty of Science, Taibah University, Almadinah Almunawwarah, Saudi Arabia* SAMIR AL SHARIFF, *Electrical Engineering Department, Faculty of engineering, Taibah University, Almadinah Almunawwarah, Saudi Arabia* Atmospheric pressure air cold plasma jet is introduced in this work. It is AC (60 Hz to 20 kHz) cold plasma jet in air. The system is consisted of a cylindrical alumina insulator tube with outer diameter of 1.59 mm and 26 mm length and 0.80 mm inner diameter. AC sinusoidal high voltage was applied to the powered electrode which is a hollow needle inserted in the Alumina tube. The inner electrode is a hollow needle with 0.80 mm and 0.46 mm outer and inner diameters respectively. The outer electrode is grounded which is a copper ring surrounded the alumina tube locates at the nozzle end. Air is blowing through the inner electrode to form a plasma jet. The jet length increases with flow rate and applied voltage to reach 1.5 cm. The gas temperature decreases with distance from the end of the nozzle and with increasing the flow rate. The spectroscopic measurement between 200 nm and 900 nm indicates that the jet contains reactive species such as OH, O in addition to the UV emission. The peak to peak current values increased from 6 mA to 12 mA. The current voltage waveform indicates that the generated jet is homogenous plasma. The jet gas temperature measurements indicate that the jet has a room temperature.

10:30

DT2 3 A Statistical Photon Transport Model: Application to Streamer Discharges in Dry Air* ZHONGMIN XIONG, MARK J. KUSHNER, *University of Michigan* Photon transport and photo-ionization are necessary to advancing propagation of positive streamer discharges by providing seed electrons. Although plasma hydrodynamics may be well represented by local transport, photon transport is intrinsically non-local. On short time and spatial scales, photon transport may also be statistical which in turn may be partly responsible for streamer branching. In this paper we discuss results from a computational investigation of the consequences of statistical radiation transport and photoionization on streamer propagation. Radiation transport in *nonPDPSIM*, the model for this study, uses a continuum approach in which photon flux from each emitting node is isotropic and every node within its absorption length receives flux. In reality, during any given time step photon emission may not be large enough for every node to receive a photon. To better reflect the statistical nature of photon transport, the emitted photon flux was discretized into particle-like packets which are isotropically but randomly emitted within a given solid angle. The time averaged flux is isotropic and all nodes within the absorption sphere receive flux, but in a statistical manner which allows for statistically long mean-free-paths. This model has been applied to simulations of positive streamer discharges in atmospheric-pressure, dry air with ns rise time voltage pulses. The results demonstrate that the statistical nature of photon transport producing stochastically distributed seeds of preionization, can be responsible for the branching of positive streamers.

10:45

DT2 4 Measurement of activated species generated by AC power excited non-equilibrium atmospheric pressure Ar plasma jet with air engulfment KEIGO TAKEDA, KENJI ISHIKAWA, HIROMASA TANAKA, *Graduate School of Engineering, Nagoya University* HIROYUKI KANO, *NU Eco-Engineering, Co., Ltd.* MAKOTO SEKINE, MASARU HORI, *Graduate School of Engineering, Nagoya University* Non-equilibrium atmospheric pressure plasma jet (NEAPPJ) is very attractive tool for bio and medical applications. In the plasma treatments, samples are typically located at a far region from main discharge, and treated in open air without purge gases. Influence of air engulfment on generation of activated species in the NEAPPJ in open air is a large issue for the application. In this study, the AC excited argon NEAPPJ with the gas flow rate of 2 slm was generated under the open air condition. The densities of the grand state nitrogen monoxide (NO) and the ground state O atom generated by the NEAPPJ were measured by laser induced fluorescence spectroscopy and vacuum ultraviolet absorption spectroscopy. The length of the plasma jet was around 10 mm. Up to 10 mm, the NO density increased with increasing the distance from plasma head, and then saturated in remote region of plasma. On the other hand, the O atom density decreased from 10^{14} to 10^{13} cm^{-3} with increasing the distance. Especially, the amount of decrease in O atom density became the largest at the plasma edge. We will discuss the generation and loss processes of activated species generated in the NEAPPJ with the measurement results using spectroscopic methods.

11:00

DT2 5 Diagnostics of the Cold Atmospheric Plasma Jet DAVID SCOTT, YASH JAIN, ALEXEY SHASHURIN, MICHAEL KEIDAR, *The George Washington University* Cold atmospheric plasmas (CAP) may have the ability to improve cancer treatment, though the mechanisms of which are yet to be fully understood To this end a better understanding of the CAP physics is required. Recent works have shown that Raleigh microwave scattering (RMS) can successfully be used to obtain the absolute value of the electron density in CAP. The fabrication and calibration of an atmospheric condition RMS apparatus to estimate electron density has recently been completed. The plasma electron density will be analyzed with varying gas mixtures, flow rates, and input power frequencies. Helium and oxygen will comprise the preponderance of input gases. The plasma gun is made of a Pyrex syringe and yields plasma with a diameter of 3 mm and length of 2 – 4 cm. In addition, a novel CAP extension has been fabricated that will yield a plasma with 1.25 mm diameter via flexible conduit. This design is intended for in-vitro CAP treatment of cancer cells. The electron density of this in-vitro apparatus will also be analyzed under varying input conditions. Photographing via an intensified charged-coupled device will be performed concurrently with density measurements in order to analyze the life-cycle of the CAP, including the streamer head and afterglow regions.

11:15

DT2 6 Pressure dependence of electrical breakdown in water vapour COLIN KELSEY, BILL GRAHAM, KEN STALDER, TOM FIELD, DAVID PATTON, TOM GILMORE, *Centre for Plasma Physics, Queens University of Belfast* The relationship of breakdown voltage to the electric field strength and number density of a gas is a fundamental part of plasma physics. It is well studied and understood for parallel plate geometries where the relationship is described by Paschen's Law and thousands of experiments have been performed to measure such curves under a wide variety of conditions. Here we produce a plasma by applying a voltage in a point to plane geometry in a conducting liquid. Shadowgraph images show a vapour layer forming on the point and subsequent light emission indicates plasma creation within the vapour. However the processes are not spatially or temporally reproducible. In order to

gain further understanding of the underlying physics of the plasma formation we are determining the electric field strength with at the aid of simulations,* experimentally determining the breakdown voltage and varying the gas density by performing the experiments and simulations at different pressures. Preliminary results indicate electric field strengths of about 10^7 V/m and that the plasma persists throughout voltage pulses of up to 2 ms.

*L. Schaper PSST. 20 (2011) 034003.

11:30

DT2 7 Electron properties of the plume of an atmospheric pressure helium plasma jet WAMEEDH ADRESS, ELENA NEDANOVSKA, GAGIK NERSISYAN, DAVID RILEY, WILLIAM GRAHAM, *Centre for Plasma Physics, Queen's University Belfast, UK* Atmospheric pressure plasma, APP, jets, are now attracting great interest because of their potential uses in many applications; for example surface modification and plasma medicine. These applications require an insight into their plasma chemistry, which is strongly influenced by the electron energy distribution function. Here we report the use of Thomson scattering to measure the electron properties in the plume created by a 20 kHz, 2mm diameter helium APP jet operating into the open air. A 532 nm Nd:YAG laser beam is focussed into the plasma plume. The temporally and spatially resolved spectra of light at 90° to the laser direction is detected. The spectra contain light from Thomson Scattering from electrons, along with Rayleigh and Raman scattering from atoms and molecules. These components are resolved in a manner similar to that described in ref 1. Our measurements reveal a "ring-like" radial distribution of both the electron density and temperature, with outer values of $\sim 7 \times 10^{13}$ cm^{-3} and 0.4 eV and inner values of $\sim 2 \times 10^{13}$ cm^{-3} and 0.1 eV respectively at 4 mm from the end of the quartz tube.

[1] A. F. H. van Gessel *et al.* Plasma Sources Sci. Technol. 21 (2012) 015003.
[2] D.Breden *et al.* Appl. Phys. Lett. 99 (2011) 111501.

11:45

DT2 8 ABSTRACT WITHDRAWN

SESSION DT3: LIQUIDS I
Tuesday Morning, 1 October 2013; Room: Nassau Room at 10:00; Mikhail Shneider, Princeton University, presiding

Invited Papers

10:00

DT3 1 Microplasmas in liquids
DAVID STAACK, *Texas A&M University*

Plasma discharges from 1 μm to 10 μm in size can be generated in a variety of liquids by the use of nanosecond duration high voltage pulses of low energy. Through a variety of high temporal and spatial resolution diagnostic the plasma discharge formation, growth and properties are studied. Experiments reveal the plasma is confined inside of a small lower density region, or bubble, in the fluid. This bubble is generated commensurate with the plasma formation and the stability and rate of bubble growth is input energy and medium dependent. Emission spectroscopy indicates the microscale plasmas to be non-equilibrium but only when the lowest energy, and smallest, discharges are generated. The non-equilibrium and high surface to volume ratio of the microplasmas offers a unique set of liquid phase plasma chemistries. Various schema for generating both highly localized and volumetrically distributed non-equilibrium microplasmas in liquids are presented. When applied to the reforming of fuels and oils the advantages of the non-equilibrium discharge in liquid regime lead to more control over the product compositions.

10:30

DT3 2 Tutorial on underwater electrical discharges: main features and applications
YAKOV KRASIK, *Physics Department, Technion*

Main features of underwater electrical discharge with short description of models ("bubble", "explosive emission", "ionization" and "thermal"), parameters of the discharge (threshold electric field versus polarity, time duration, frequency, pressure, interelectrode gap and area of electrodes, velocity of streamer propagation and density and temperature of the plasma, strong shock waves) and different electrical and optical diagnostics which were used in this research will be shortly reviewed. Such main applications of underwater electrical discharge as electro-hydraulic forming, destruction of rocks, low-inductance water spark gap switches, treatment of pollutants in water and extracorporeal shock wave lithotripsy will be discussed. Finally, results of application of underwater electrical explosion of single wires in nanosecond - microsecond timescales for research related to Equation of State of different materials at extreme conditions and underwater electrical explosion of wire arrays in cylindrical and spherical configurations for generation of converging strong shock waves using moderate high-power generators for research of compressed water at extreme conditions will be presented.

Contributed Papers

11:15

DT3 3 Nanosecond Pulsed Discharges in Liquid Phase: Optical diagnostics of positive versus negative modes of initiation in water* YOHAN SEEPERSAD, ALEXANDER FRIDMAN, DANIL DOBRYNIN, *A.J. Drexel Plasma Institute, Camden, NJ 08103, USA* APPLIED PHYSICS GROUP TEAM   Recent work on nanosecond pulsed discharges in liquids has shown the possibility of producing plasma directly in the liquid phase without bubble formation or heating of the liquid. Paramount to understanding the physical processes leading to this phenomenon is a thorough understanding of the way these discharges behave under various conditions. This work explores the development of nanosecond pulsed discharges in water, for both positively and negatively applied pulses in a pin-to-plane configuration. Time resolved nanosecond ICCD imaging is used to trace the development of the discharge for applied voltages up to 24 kV. From the results we are able to identify breakdown thresholds at which discharge is initiated for both modes. At voltages below the critical breakdown value, Schlieren and shadowgraphy techniques are used to investigate perturbations in the liquid layers near the electrode tip as a consequence of these fat rising pulses.

11:30

DT3 4 Plasma Spark Discharge Generated Water Displacement
NATHANIEL TAYLOR, *Drexel University* DANIL DOBRYNIN, *A.J. Drexel Plasma Institute* ALEXANDER FRIDMAN, *Drexel University* The physical displacement of water generated by plasma spark discharge has been investigated to determine the correlation between discharge parameters and displacement. Microsecond duration spark discharge pulses generate shockwaves and vapor which subsequently displaces the fluid over a period of milliseconds. Pulses ranging from 18 to 28 kV are generated inside of a sealed chamber and observed using a glass monometer. The displacement of the water has been measured using high-speed ICCD imagery and correlated to the plasma discharge energy and duration.

11:45

DT3 5 Mechanism of efficient production of standing sonoplasmas with the help of a punching metal plate K. SASAKI, Y. IWATA, S. TOMIOKA, S. NISHIYAMA, *Hokkaido University* N. TAKADA, *Nagoya University* We have reported an efficient method for producing standing sonoplasmas. This method employs a punching metal plate which is inserted just below the water surface with the irradiation of ultrasonic wave. In this work, we carried out two experiments to investigate the mechanism of the efficient production of standing sonoplasmas. One was the measurement of the intensity distribution of the ultrasonic wave using an optical microphone. As a result, it was found that, at the optimum depth of water for producing sonoplasmas, the intensity of the ultrasonic wave was strong in the neighboring region to the water surface where the punching metal plate was inserted. In addition, we observed a local minimum in the distribution of the ultrasonic wave intensity. The location of the local minimum coincided with the standing point of cavitation bubbles or sonoplasmas. The other experiment was the shadowgraph imaging of cavitation bubbles. As a result, we found the efficient formation of seed bubbles in the adjacent region to the punching metal plate. The seed bubbles were transported to the local minimum of the ultrasonic wave intensity. We will discuss the mechanism of the efficient production of standing sonoplasmas on the basis of these experimental observations.

SESSION DT4: WORKSHOP ON THE MYSTERIES AND CHALLENGES OF NEGATIVE ION SOURCES
Tuesday Morning, 1 October 2013
Room: Fountain View at 10:00
Robert Welton; Larry Grisham; Rod Boswell, Oak Ridge National Laboratory; Princeton Plasma Physics Laboratory; Australia National University, presiding

Contributed Papers

10:00

DT4 1 Introduction ROB WELTON,

10:10

DT4 2 The requirements and challenges of the next generation negative ion sources OLLI TARVAINEN, *University of Jyvaskyla, Department of Physics* Negative ion sources are often subsystems of particle accelerators and neutral beam injectors. Thus, the requirements of the next generation negative ion sources are largely driven by upgrades and new developments of these technologies. The performance of negative ion sources is typically defined by the beam current and emittance, long and short-term stability of the extracted beams, the ratio of desired ions to co-extracted electrons and the maintenance interval of the ion source. The requirements of the next generation negative ion sources in each of these categories are described and compared to the state-of-the-art technologies. The

physics of negative ion production are discussed briefly to outline the fundamental and technical challenges of the future negative ion sources. An overview of their development effort will be given with the main focus being in H^-/D^- ion sources, which are currently under active research and development in several laboratories. Some novel ideas and techniques to improve the performance of negative ion sources are described to facilitate discussion.

10:50
DT4 3 Challenges of negative hydrogen ion sources for fusion URSEL FANTZ, *Max-Planck-Institut fuer Plasmaphysik, EU-RATOM Association, Boltzmannstr. 2, 85748 Garching, Germany* The neutral beam injection systems for the international fusion experiment ITER (www.iter.org) are based on large negative hydrogen ion sources which have to operate at very ambitious parameters. They have to deliver an accelerated current of 40 A negative hydrogen ions extracted from 1280 apertures stable for one hour. The co-extracted electron current has to be kept below the extracted ion current to avoid damages of the grid system. At the source pressure of 0.3 Pa or below the negative ions have to be produced at a surface with low work function for which cesium is evaporated into the source. In order to fulfill all these requirements an R&D program has been launched several years ago. The challenges, however, are enormous; among them the control of the cesium dynamics in the source which determines the reliability of the source performance, the amount of co-extracted electrons which limits the extractable negative ion current, and the size scaling of the source towards an area of 1.9×1 m^2. Among the open and less understood issues are the magnetic filter field (initially used to reduce the electron temperature and density) in combination with the biasing of the grid surface, the sensitivity of the co-extracted electrons on cesium, the high co-extracted electron current in deuterium, and the fortunately weak correlation of the plasma homogeneity with the beam homogeneity. The present status, the most critical issues and open and less understood issues will be addressed and may serve as a trigger for a stimulating discussion or even trigger experiments and modeling activities to these topics.

11:30
DT4 4 LUNCH

13:00
DT4 5 DISCUSSION

13:30
DT4 6 Challenges/issues of NIS used in particle accelerator facilities DAN FAIRCLOTH, *Rutherford Appleton Laboratory* High current, high duty cycle negative ion sources are an essential component of many high power particle accelerators. This talk gives an overview of the state-of-the-art sources used around the world. Volume, surface and charge exchange negative ion production processes are detailed. Cesiated magnetron and Penning surface plasma sources are discussed along with surface converter sources. Multicusp volume sources with filament and LaB6 cathodes are described before moving onto RF inductively coupled volume sources with internal and external antennas. The major challenges facing accelerator facilities are detailed. Beam current, source lifetime and reliability are the most pressing. The pros and cons of each source technology is discussed along with their development programs. The uncertainties and unknowns common to these sources are discussed. The dynamics of cesium surface coverage and the causes of source variability are still unknown. Minimizing beam emittance is

essential to maximizing the transport of high current beams; space charge effects are very important. The basic physics of negative ion production is still not well understood, theoretical and experimental programs continue to improve this, but there are still many mysteries to be solved.

14:10
DT4 7 Challenges in plasma and extraction modelling of negative ion sources TANELI KALVAS, *University of Jyvaskyla* The physical processes taking place in negative ion source plasmas are modelled by state-of-the-art 3D particle-in-cell (PIC) codes. These codes are used to gain understanding and to find optimal solutions for negative ion beam production. The PIC codes can be made to match to the reality if all relevant processes were included. This is unfortunately limited by the availability of data about the processes and the huge amount of computational resources needed for the simulations. The optimization of the extraction system and beam transport ion optics is often made using computationally less intensive methods utilized in so-called gun codes. These codes use simplified plasma models to provide a starting point for the extracted beams being simulated. The relatively fast computation allows systematic studies, which are not practical with PIC codes. The gun codes often match well to reality, but they do have difficulties reproducing some effects, especially in negative ion extraction, due to the approximations made in the plasma model. Could the future solutions for beam production modelling couple the two types of simulations?

14:50
DT4 8 BREAK

15:30
DT4 9 DISCUSSION

16:10
DT4 10 Unresolved problems in cesiation processes of negative hydrogen ion sources MOTOI WADA, *School of Science and Engineering, Doshisha University* Attempts are being made to optimize negative hydrogen (H^-) ion current by introducing Cs into an ion source, but there are some unanswered questions in properly handling Cs to realize stable extraction of H^- ion beams. For example, Cs amount to optimize H^- production often becomes much larger than the amount predicted to realize partial monolayer of Cs on the source wall. Additional charge of Cs into a source to recover reduced H^- current by continuous operation does not necessarily realize the original value. Beam intensity of H^- changes with the impurity content in the ion source. The purpose of the present paper is to list up these uncertainties and unknown factors in negative ion source performance operated with Cs. The paper tries to identify possible mechanisms causing these problems by running a simulation code ACAT (Atomic Collision in Amorphous Target). The code predicts that glancing injection of hydrogen ions doubles the numbers of both reflection coefficients and ion induced desorption yields from those for the normal incidence. It also indicates smaller hydrogen desorption yields for thick layer of adsorbed hydrogen on the surface. These results are compared with experimental data obtained in UHV conditions.

16:50
DT4 11 DISCUSSION

17:30
DT4 12 Closing Remarks LARRY GRISHAM,

Contributed Papers

13:30

ET1 1 Properties of linear microwave plasma sustained by coaxial TEM waveguide MOON-KI HAN, KWON-SANG SEO, DONG HYUN KIM, HAE JUNE LEE, HO-JUN LEE, *Department of Electrical Engineering, Pusan National University, Busan 609-735* A linear 2.45GHz microwave plasma sustained by coaxial circular TEM waveguide has been developed for the low temperature large area plasma enhanced chemical vapor deposition application. TE-TEM microwave power coupling was achieved by copper rod located at $\lambda_g/4$ from short-end of TE_{10} waveguide. TEM waveguide consists of quartz tube surrounded by plasma and copper rod electrode. TEM waveguide is 60 cm in length and 3 cm in diameter, which is terminated with shorted metal cap. For the operation condition of 300 W input power and Ar pressure of 200 mTorr, a clear standing wave pattern with wavelength of 10 cm was observed. Measured plasma density and temperature at 5 cm from quartz wall was $1.2 \times 10^{17}/cm^3$ and 1.7 eV respectively. Density non-uniformity was less than 6% along quartz tube in spite of standing wave set-up. In addition, properties of the microwave source are also investigated through electromagnetic field simulation coupled with drift-diffusion approximation of plasma. Calculated and measured standing wave pattern was almost identical. Electron density and temperature distribution show similar behavior with experimental results. S_{11} value of input port of TE_{10} waveguide was calculated as 17dB.

13:45

ET1 2 Kinetic simulation of subnanosecond current front rise in high-voltage pulse open discharge IRINA SCHWEIGERT, *Institute of Theoretical and Applied Mechanics, SB RAS* A.L. ALEXANDROV, *ITAM SB RAS* P. A. BOKHAN, DM. E. ZAKREVSKY, *A.V. Rzhanov Institute of Semiconductor Physics, SB RAS* Generation of high-power electrical pulses with nanosecond front rise times is widely used in various applications. In this work in kinetic simulation we study the switching performance of moderate-pressure open discharge in helium for the experimental conditions [1]. The discharge ignition (with current front rises) takes place during time t < 1 ns after applying few kilovolts voltage. This phenomenon of high-efficiency generation of electron beams was studied previously and based on the effect of runaway of electrons. The discharge has a plane geometry and glows in a narrow gap (of width less than 1 cm) between two cathodes and a grid anode between them. The mechanism providing the high-efficiently electron generation is related to the fast excitation of atoms and transport of the photons to the cathodes without reabsorption. In calculations, the motion of electrons, ions and fast neutrals is simulated, solving the kinetic equations and Poisson equation with PIC MCC method self-consistently. The ionization and excitation of atoms takes place after collisions of neutrals with electrons, ions and fast neutrals.

[1]P. A. Bokhan, P. P. Gugin, M. A. Lavrukhin, and Dm. E. Zakrevsky, Phys. Plasma, **20**, 033507 (2013).

14:00

ET1 3 Bifurcation of electron density in microwave plasma source with negative-permeability metamaterial OSAMU SAKAI, YOSHIHIKO NAKAMURA, *Kyoto University* High electron-density plasmas beyond cutoff density were generated by high-power microwaves in a negative-permeability space, in which negative permittivity achieved in high density plasma makes refractive index real and negative. Experimental results using a high power microwave source and negative-permeability metamaterials verify that this plasma generation is in bifurcated states: high density and low density cases. This indicates that the process is quite nonlinear, partly predicted by our previous study [1]. When we made the permeability positive, we did not see such clear bifurcations. Furthermore, after high-density plasma generation, transmitted microwaves increased, which is quite abnormal in usual microwave plasma sources. Our previous report [2] demonstrates "plasma metamaterials" which include array of microplasmas and metallic microstructures with functional roles as media of electromagnetic waves with small amplitudes. The state of plasmas generated by high-power microwaves and immersed in the metallic metamaterial microstructures will open novel functions of plasma metamaterials; they are nonlinear metamaterials for scientific interests, potential high-density microwave sources for plasma processing, and potential switches for high-power microwaves.

[1]O. Sakai *et al.*, J. Appl. Phys. vol. 109 (2011) 084914.
[2]O. Sakai *et al.*, Plasma Sources Sci. Technol., vol. 21 (2012), 013001.

14:15

ET1 4 Plasmas created by UV illumination rather than electron impact RAOUL FRANKLIN, *The OpenUniversity* Some of the early experimental work in fusion concerned itself with problems of current limitation and neutral gas depletion, and so was carried out in mercury gas discharges at very low pressures. We return to such a situation and examine it where the plasma is generated by ultra-violet illumination in mercury and develop equations to describe it. The cases of full illumination and partial illumination are considered. These equations are not very different from those conventionally used to describe low pressure gas discharges, but when examined in different geometries throw up problems not necessarily anticipated. So we have examined the situation in different geometries, stimulated by the fact that in the unilluminated region in the quasi-neutral approximation gives rise to a plasma of undefined extent with uniform density and constant drift speeds. We have obtained results in cylindrical geometry, which we believe are asymptotically correct and describe such plasmas.

14:30

ET1 5 Resonance Ionization Instability in HF and Microwave Discharges SERGEY DVININ, *Lomonosov Moscow State University* VITALIY DOVZHENKO, *A.M. Obukhov Institute of Atmospheric Physics RAS* For the first time ionization instability of HF plasma has been described in [1]. Later it has been shown [2] that in the spatially limited low pressure microwave discharge the given instability leads not only to change plasma structure, but to appearance of resonances at electron densities, when the size of plasma becomes multiple to some number of half waves of the standing surface wave, exciting on plasma boundary. Evolution of electron density perturbation is defined by two processes – negative feedback owing to a total current continuity (as in striations) and positive one due to excitation of a wave, which is close to a resonance. In the given work the theory [2] has been improved

with accounting of both processes that has allowed to reach better coincidence with experiment [3]. In addition, the general theory of ionization instability has been developed. Application of the model to CCP HF (100 MHz and higher) discharge with large electrodes has shown that excitation of the instability accompanied by surface waves, propagating along plasma-sheath-electrodes interface, is possible.

[1] V.B. Gildenburg and A.V. Kim, XI ICPIG. Berlin 273 (1976).
[2] S. Dvinin et al., Sov. Phys.: Fizika Plazmy, **8**, 1228 (1982), **9**, (1983).
[3] S. Dvinin et al., Sov. Phys.: Fizika Plazmy, **9**, 1297 (1983).

14:45
ET1 6 A two-dimensional plasma model for a coaxial microwave discharge* SARA RAHIMI, MANUEL JIMENEZ-DIAZ, SIMON HÜBNER, EFE H. KEMANECI, JOOST J.J.A VAN DER MULLEN, JAN VAN DIJK, *Department of Applied Physics, Eindhoven University of Technology* We present a two-dimensional plasma model for a coaxial microwave discharge. The microwave energy at driving frequency of 2.45 GHz is fed into a coaxial configuration in which the plasma acts as an outer conductor in such a way that a spatially extended surface wave is created. This geometry permits large surface treatment especially if a set of such coaxial lines is used. The 2D model based on the Plasimo toolkit describes the coaxial discharge self consistently. The model for argon as working gas is validated with experimental results for the electron density and temperature obtained by Thomson Scattering. The model is implemented for SiH4/H2 and is used to study the influence of various working conditions.

SESSION ET2: MICRODISCHARGES I
Tuesday Afternoon, 1 October 2013
Room: Ballroom II at 13:30
Fumiyoshi Tochikubo, Tokyo Metropolitan University, presiding

Contributed Papers

13:30
ET2 1 Electrical Breakdown Characteristics in Fluctuating Fluids near Gas-liquid Critical Point of Helium* HITOSHI MUNEOKA, KEIICHIRO URABE, SVEN STAUSS, KAZUO TERASHIMA, *The University of Tokyo* In order to unify discharge behavior in gases and liquids, we have experimentally investigated the breakdown voltages near the critical point of helium [critical temperature (T_c): 5.20 K, critical pressure (P_c): 0.227 MPa], for $T = 5.02$ - 5.50 K and $P = 0.03$ - 0.3 MPa, which includes the gaseous, liquid, and supercritical fluid (SCF) states of helium. Detailed measurements of micrometer-gap (~ 3 μm) direct-current discharges in the high density (0.1 – 27 mol/L) and ultra-pure (due to the very low temperature) medium allowed for the first time a clear observation of a critical anomaly of the breakdown voltage in helium. This anomaly - a local minimum of the breakdown voltage - could only be observed in micrometer gap discharges because the characteristic length of the local fluid structure has to be comparable

to the gap distance. We also developed a discharge model that takes into account the local fluid structure in a fluctuating medium and the effect of small discharge volumes. The analysis and model suggest that the critical anomaly is caused by extended acceleration paths inside low density domains generated by the density fluctuation.

13:45
ET2 2 Self-Pulsing Non-Equilibrium Plasma Discharge at Atmospheric and Higher Pressures RAJIB MAHAMUD, *Graduate Research Assistant, Department of Mechanical Engineering, University of South Carolina* TANVIR I. FAROUK, *Assistant Professor, Department of Mechanical Engineering, University of South Carolina* Recently there has been research trust directed towards the development of high pressure non-thermal plasma with a focus to overcome the limitations of their low pressure counter parts. Among the different high pressure non-thermal discharges *micro plasma* continues to be a topic of immense interest. Even though micron sized inter-electrode separation has been successful in attaining non-thermal plasma conditions at atmospheric pressure, the small size cause the effect of other operating parameters to be crucial in stable operation. In this study, simulation of DC micro plasma discharge has been conducted using a hybrid model with detailed helium-nitrogen feed gas kinetics. Simulations were conducted over a broad range of pressure 1 – 10 atm, and power circuit parameters. The self-pulsing regime was found to operate in the subnormal regime and is triggered when the circuit response time starts becoming comparable and larger than the ion transit time. The simulations further indicated that the oscillation frequency increases as the discharge current increases in the subnormal regime. In this self-pulsing regime of operation insignificant increase in the gas temperature is observed confirming that the self-pulsing is not due thermal instability. Results from the study showed that this self-pulsing mode is more prevalent at higher pressure. The oscillation frequency increased almost in a linear fashion as a function of pressure. Predictions were found to be good agreement with experimental measurements.

14:00
ET2 3 A short pulse, high rep-rate microdischarge VUV source* JACOB STEPHENS, ANDREW FIERRO, JAMES DICKENS, ANDREAS NEUBER, *Texas Tech University* CENTER FOR PULSED POWER AND POWER ELECTRONICS TEAM A MOSFET based high voltage pulser is utilized to excite a microdischarge (MD), or microdischarge array (MDA) with pulsed voltages of up to 1 kV, with risetime and FWHM on the order of 10 ns and 30 ns, respectively. Additionally, the pulser is capable of pulsing at rep-rates in excess of 35 MHz. However, for these experiments the rep-rate was set on the order of 1 MHz, so as to limit excess energy deposition into the background gas and optimize the energy efficiency of VUV generation. Using VUV capable spectral diagnostics, the VUV emission of the MDs for various pressures (50-800+ Torr) and gases, focused on argon, argon-hydrogen mixtures, and neon-hydrogen mixtures (all of which provide strong emission at $\lambda < 130$ nm) is studied, for pulsed, MHz rep-rated excitation. Using a photomultiplier tube the time dependent behavior of the VUV emission is characterized and compared to results from transient fluid modeling of the MDA. For instance, the MDA turn-on time is

recorded to be about 15 ns, which matches the full plasma development time in the model, and the MDA self- capacitance largely determines the turn-off behavior.

14:15
ET2 4 Laser-spectroscopic electric field measurements in a ns-pulsed microplasma in nitrogen* PATRICK BOEHM, DIRK LUGGENHOELSCHER, UWE CZARNETZKI, *Ruhr-University Bochum* FOR 1123 RESEARCH GROUP COLLABORATION In this work for the first time ns-pulsed discharges in nitrogen at near atmospheric pressures are investigated by laser-spectroscopic electric field measurements, ultra-fast optical emission spectroscopy, current and voltage measurements. The discharge is operated with kV-pulses of about 150 ns duration between two parallel plate electrodes with a 1.2 mm gap. The laser technique for electric field measurement is based on a four-wave mixing process similar to Coherent anti-Stokes Raman Scattering (CARS). Here the static electric field acts effectively as the third wave with a zero frequency. The frequency of the generated anti-Stokes wave is in the IR regime and the amplitude is proportional to the electric field strength. By measuring the intensity of the IR- and anti-Stokes-signal it is now possible to determine the static electric field. Due to the short pulse-length of the lasers a temporal resolution in the ns range and a typical sensitivity of 50 - 100 V/mm in pure nitrogen is achieved ($p > 50$ mbar). Field-measurements are accompanied by emission measurements using a streak-camera with sub-ns resolutions. Further, current and voltage measurements combined with the electric field measurements allow determination of the plasma density.

14:30
ET2 5 Implementation of a 3D PIC/MCC Simulation to Investigate Plasma Initiation in Nitrogen at Atmospheric Pressure* ANDREW FIERRO, JAMES DICKENS, ANDREAS NEUBER, *Texas Tech University* The particle-particle interactions involved in plasma formation are well suited to implement in a parallel environment due to the identical computations done for each particle. Specifically, a 3D PIC/MCC simulation was accelerated on an NVIDIA graphics processing unit (GPU) using the CUDA framework for a developing plasma in nitrogen gas at atmospheric pressure to study the initial phase of breakdown. For this simulation, the computational volume was $\sim$220 mm^3 with 15 μm spatial resolution containing two parabolic electrodes. The plasma development is typically characterized by the development of positive ion space charge creating a localized field enhancement thus accelerating ionization processes in this region. For instance, with the application of an 8 kV/cm electric field amplitude, after 1 ns into the simulation, the development of positive ion space charge near both anode and cathode is observed with the densities of $\sim 10^{16}$ cm^{-3} and $\sim 10^{14}$ - 10^{15} cm^{-3}, respectively, while the electron density sits at $\sim 10^{11}$ cm^{-3}. Already 100 ps into the simulation, the distribution of electron energies exhibits non-thermal characteristics with an average electron energy of 0.98 eV that increases to $\sim$10 eV at 1 ns.

14:45
ET2 6 DC Pulsed Atmospheric Micro Plasma using a Voltage Doubled Capacitive Ballast* CHANG-SEUNG HA, JE-HYUN LEE, EUI-JEONG SON, DONG-HYUN KIM, HAE JUNE LEE, HO-JUN LEE, *Department of Electrical Engineering, Pusan National University* PPRC TEAM An atmospheric plasma driven by the capacitive ballast circuit with voltage doubler has been developed. At first, the capacitors are charged and then the stored energy is injected into the electrode. At that time, the voltage is doubled by means of series connection switching. The switching device isolate the power from the plasma, therefore the discharge energy is effectively controlled by the stored energy in the capacitor. The role of voltage doubler is maintaining the charging voltage less than the firing voltage of the electrodes and providing sufficiently high voltage during the plasma generation. It eliminates parasitic discharge due to capacitive coupling between isolation switch and plasma electrodes. Proposed method allows stable operation of the μ-plasma under dielectric-free electrode as well as independent control of discharge voltage and energy. When the applied capacitance is varied as 1.2 nF, 10 nF and 22 nF at the voltage of 600V, the corresponding discharge energy per pulse is 168 μJ, 971 μJ, and 1.126 mJ respectively. For the fixed capacitance value, discharge duration decreases and peak current increases with the discharge voltage. The characteristics of the micro plasma are analyzed in terms of time-resolved images, spatio-temporally resolved OES and fluid simulations.

SESSION ET3: GREEN PLASMA TECHNOLOGIES I
Tuesday Afternoon, 1 October 2013; Room: Nassau Room at 13:30; Mohan Sankaran, Case Western Reserve University, presiding

Invited Papers

13:30
ET3 1 Plasma enhanced C1 chemistry for green technology
TOMOHIRO NOZAKI, *Department of Mechanical Sciences and Engineering, Tokyo Institute of Technology*

Plasma catalysis is one of the innovative next generation green technologies that meet the needs for energy and materials conservation as well as environmental protection. Non-thermal plasma uniquely generates reactive species independently of reaction temperature, and these species are used to initiate chemical reactions at unexpectedly lower temperatures

than normal thermochemical reactions. Non-thermal plasma thus broadens the operation window of existing chemical conversion processes, and ultimately allows modification of the process parameters to minimize energy and material consumption. We have been specifically focusing on dielectric barrier discharge (DBD) as one of the viable non-thermal plasma sources for practical fuel reforming. In the presentation, room temperature one-step conversion of methane to methanol and hydrogen using a miniaturized DBD reactor (microplasma reactor) is highlighted. The practical impact of plasma technology on existing C1-chemistry is introduced, and then unique characteristics of plasma fuel reforming such as non-equilibrium product distribution is discussed.

Contributed Papers

14:00

ET3 2 Development of a high mass-transfer dielectric barrier discharge reactor dedicated to the degradation of persistent organic pollutants in water OLIVIER LESAGE, *Laboratoire de genie des procedes plasma et traitement de surface, France / Laboratoire de biomateriaux et bioingenierie, Canada* JEAN-MARC COMMENGES, *Laboratoire des Reactions et Genie des Procedes, France* WILLY MORSCHEIDT, *Laboratoire de genie des procedes plasma et traitement de surface, France* XAVIER DUTEN, *Laboratoire des Sciences des Procedes et Materiaux, France* MICHAEL TATOULIAN, SIMEON CAVADIAS, STEPHANIE OGNIER, *Laboratoire de genie des procedes plasma et traitement de surface, France* Some organic compounds such as pCBA are refractory to ozone oxidation. In that context, an AOP based on the use of a dielectric barrier discharge (DBD) working in air at atmospheric pressure has been developed. The process consists in a Thin Falling Film Plasma Reactor (TFFPR) where a discharge is created in the gaseous gap between a high voltage electrode and the surface of the water to treat. To improve radical species transfer, a microstructured plate was used to obtain a thin water film flow. Solution of pCBA was treated in the TFFPR with two different plates (SS316L and Brass). The concentrations of pCBA, NO3- and NO2- were measured using liquid chromatography. To understand the influence of the surface of the material, the NOx concentration on the gas phase and to quantify the flux of HO, we made a simulation with a CFD code. Our results indicated that the DBD directly in contact with liquid can be efficient to oxidize persistent molecules (80% after 30 min) and are brought out the production of HO in the liquid phase. Indeed, the simulation showed that 50% of HO are trapped by NO2-. The efficiency can be increasing by avoiding NOx formation. For brass, the efficiency is reduced to 50% due to corrosion reactions of the material.

14:15

ET3 3 Study of organic pollutants oxidation by atmospheric plasma discharge DIANE GUMUCHIAN, *Laboratoire de Genie des Procedes Plasma et Traitements de Surface/Institut Jean le Rond d'Alembert* SIMEON CAVADIAS, *Laboratoire de Genie des Procedes Plasma et Traitements de Surface* XAVIER DUTEN, *Laboratoire des Sciences des Procedes et Materiaux* MICHAEL TATOULIAN, *Laboratoire de Genie des Procedes Plasma et Traitements de Surface* PATRICK DA COSTA, *Institut Jean Le Rond d'Alembert* STEPHANIE OGNIER, *Laboratoire de Genie des Procedes Plasma et Traitements de Surface* Ozonation is one of the usual steps in water treatment processes. However, some organic molecules (acetic acid) cannot be decomposed during ozonation. In that context, we are developing an Advanced Oxidation Process based on the use of a needle plate discharge at atmospheric pressure. The process is a reactor with a plasma discharge between a high voltage electrode and the solution in controlled atmosphere. Characterizations of the plasma obtained in different atmospheres were carried out (Optical Emission Spectroscopy, iCCD camera

observations, etc). The efficiency of the process was evaluated by the percentage of degradation of the model-pollutant, measured by liquid chromatography analysis. Treatments in nitrogen lead to the formation of NOx species that decrease the efficiency of the process. Indeed, NOx lead to the consumption of actives species created. Treatments in argon are the most efficient. Two hypotheses are considered: (i) metastable argon participates to the degradation of acetic acid or to the formation of radicals (ii) discharges in argon lead to the formation of many streamers of low energy that increase the interface plasma/solution.

14:30

ET3 4 Hydrogen sulfide dissociation in nanosecond dielectric barrier discharge KIRILL GUTSOL, ALEXANDER RABINOVICH, *Drexel University* ALEXANDER GUTSOL, *Chevron Energy Technology Company* ALEXANDER FRIDMAN, *Drexel University* Hydrogen sulfide (H_2S) is a byproduct of oil refinement, and it comprises a large portion of natural gas deposits. The minimum dissociation energy of hydrogen sulfide is only 0.2 eV/molec, and it is very important commercially. The process of hydrogen sulfide dissociation was investigated in nanosecond dielectric barrier discharge (ns-DBD). Experiments on dissociation of H_2S in ns-DBD allows for effective separation of ion-molecular and thermal effects, which is necessary for understanding the potential and limitations of plasma dissociation of hydrogen sulfide. The study was performed in a reactor, in which there is no contact between any metal parts (including electrodes) and H_2S. It is well known that many common metals and alloys either react or catalyze H_2S dissociation (especially at elevated temperature); our reactor design eliminates this problem. This study was performed in a moderately low pressure reactor (50 - 200 Torr) with 100% pure hydrogen sulfide. The minimum dissociation energy cost was found to be less than 5 eV/molec at room temperature, which is significantly better than results obtained in earlier studies using discharges with high E/n and low gas temperature.

Contributed Papers

13:30

ET5 1 Introduction LEANNE PITCHFORD, *CNRS*

13:40

ET5 2 eMOL Evaluating electron-water scattering data NIGEL MASON, *Department of Physical Sciences, The Open University, Walton Hall, Milton Keynes, Mk7 6AA United Kingdom* The eMOL

(electron molecule) project has been established to establish the process by which such data will be reviewed, validated and recommended data sets published. In particular eMOL seeks to suggest whether any particular data set be used as a primary or secondary source of data for the wider community. Primary would mean that is judged to the best representation of that particular interaction/cross section and therefore be used as a "recommended" value for users. The first target to be reviewed by eMOL was water with 8 members of the eMOL board meeting in Vienna in May 2013. The Board used the most recent review of electron-water scattering (Itikawa and Mason J. Phys. Chem. Ref. Data 34 1-22 (2005)) as its reference point. Over 80 papers (collected and disseminated by eMOL's bibliometrician Dr D Jaksch) that had been published subsequent to this review were reviewed and recommendations made as to whether such data should replace recommendations in the earlier review. The Meeting also identified areas (cross sections) for future research, data inconsistencies and reviewed the allocation of uncertainty estimates for complete datasets (assembled from a combination of both experimental and theoretical data). In this presentation I will therefore both present the findings of this review and discuss this study as an exemplar of the wider eMOL programme which will review some 15 electron-molecule datasets in 2013-15 including many of interest to the GEC (plasma) community.

14:10

ET5 3 Electron swarms in water vapour: measurement, transport theory and cross-sections* RON WHITE, *ARC Centre for Antimatter-Matter Studies, School of Engineering and Physical Sciences, James Cook University* K.F. NESS, *ARC Centre for Antimatter-Matter Studies, School of Engine ering and Physical Sciences, James Cook University* R.E. ROBSON, *ARC Centre for Antimatter-Matter Studies, School of Engineering and Physical Sciences, James Cook University* M.J. BRUNGER, *ARC Centre for Antimatter-Matter Studies, School of Chemical and Physical Sciences, Flinders University* The determination of a comprehensive set of electron–water vapour cross-sections is fundamental to understanding electron induced processes arising in applications ranging from plasma discharges to astrophysics, planetary, terrestrial and cometary atmospheres and radiation damage modelling. Formulation of complete sets are generally based on a critical assessment of available experimental "beam" studies and theoretical calculations. Issues of completeness and accuracy of cross-section sets still remain and it is here that swarm experiments play a key role. In this presentation we assess the consistency of recent cross-section sets, particularly those including recent measurements for vibrational and electronic excitation. Comparison of calculated transport coefficients using an improved multi-term Boltzmann equation solution with the available experimental swarm measurements provides a discriminating test on consistency and accuracy of the cross-section sets. Issues associated with transport coefficient definition and experimental interpretation will be revisited and distilled.

14:40

ET5 4 Open Discussion on data need for modeling plasmas containing water vapor

15:10

ET5 5 Previews of posters in this sorting category, limited to one power point slide per poster

15:30

ET5 6 General discussion including a status report on the PDEP project and a discussion of where we want to go from here

16:00

ET5 7 Closing Remarks LEANNE PITCHFORD,

SESSION FT1: NON-EQUILIBRIUM KINETICS OF LOW-TEMPERATURE PLASMAS
Tuesday Afternoon, 1 October 2013
Room: Ballroom I at 15:30
Thomas Mussenbrock, Ruhr-University Bochum, presiding

Contributed Papers

15:30

FT1 1 Active Plasma Resonance Spectroscopy: A Kinetic Functional Analytic Description* JENS OBERRATH, THOMAS MUSSENBROCK, RALF PETER BRINKMANN, *Ruhr University Bochum* The term "active plasma resonance spectroscopy" refers to a plasma diagnostic method which employs the natural ability of plasmas to resonate close to the plasma frequency. Essential for this method is an appropriate model to determine the relation between the resonance frequencies and demanded plasma parameters. Measurements with these probes in plasmas of a few Pa typically show a broadening of the spectrum that cannot be predicted by a fluid model. Thus, a kinetic model is necessary. A general kinetic model of electrostatic resonance probes has been presented by the authors [1]. This model is used to analyze the dynamic behavior of such probes, especially the spherical Impedance Probe and the Multipole Resonance Probe. It is shown, that damped resonances occur even in collisionless plasmas. Such a collisionless damping is caused by kinetic effects and is responsible for the broadening in a measured spectrum. Thus, the solution of the kinetic model can be used to determine the relation between the broadening of the resonance peak and the "equivalent electron temperature."

[1]J. Oberrath, T. Mussenbrock, R. P. Brinkmann, arXiv: 1305.7253 [physics.plasm-ph]

15:45

FT1 2 Enhancement of the Coulomb collision rate by individual particle wakes SCOTT BAALRUD, BRETT SCHEINER, *Department of Physics and Astronomy, University of Iowa* Charged particles moving in a plasma leave a trailing wake in their electric potential profile associated with the response function of the medium. For superthermal particles, these wakes can cause significant departures from the oft-assumed screened Coulomb potential profile. The wakes extend the interaction length scale beyond the Debye screening length for collisions between fast test particles and field particles in their wake. This can increase the Coulomb collision rate for velocities beyond the thermal speed. To demonstrate this effect, we consider the relaxation rate due to electron-electron collisions of an electron distribution function with initially depleted tails, as is common near boundary sheaths or double layers. This problem is related to Langmuir's paradox. We compare the standard

Landau (Fokker-Planck) collision operator, which does not account for wakes, with the Lenard-Balescu collision operator, which includes wake effects through the linear dielectric response function. For this distribution, the linear dielectric is described by the incomplete plasma dispersion function.* We compare the collision operators directly as well as the relaxation rate determined from a hybrid kinetic-fluid model.

*S. D. Baalrud, Phys. Plasmas 20, 012118 (2013).

16:00

FT1 3 Particle Simulation of Expansion of Plasma Induced by Resonance Enhanced Multiphoton Ionization in Argon Gas SIVA SASHANK THOLETI, VENKATTRAMAN AYYASWAMY, ALINA A. ALEXEENKO, *School of Aeronautics and Astronautics, Purdue University* MIKHAIL N. SHNEIDER, *Department of Mechanical and Aerospace Engineering, Princeton University* Rayleigh scattering of plasma generated by resonance enhanced multiphoton ionization (REMPI) provides a non-intrusive, time accurate measurement of electron formation and loss with many applications in plasma diagnostics. In this paper we study the non-equilibrium processes during the expansion of REMPI plasma. The particle in cell method with Monte Carlo collision (PIC/MCC) scheme is applied to account for the micron-sized characteristic length scale of the plasma and the non-continuum nature of the fast expansion process. Both 1D and 2D approximations are considered for the REMPI plasma expansion in Argon gas generated by a laser with a focal shape of a prolate ellipsoid at 100 torr and 5 torr pressures. The expansion of the plasma is found to be very sensitive to the initial velocity distribution of the electrons. REMPI plasma expansion is shown to be ambipolar in nature. Even though the radial expansion is predominant, there is a significant axial component requiring the 2D model. The deviation of the electron energy distribution functions (EEDFs) from that of the equilibrium Maxwell-Boltzmann energy distribution is presented both qualitatively and quantitatively. Based on this analysis the distinct plasma expansion phases have been delineated at various instances in time.

16:15

FT1 4 Nitrogen atoms influence on associative ionization in nitrogen plasma ANDREY VOLYNETS,* ALEXEY ZOTOVICH,[†] *Lomonosov Moscow State University, Faculty of Physics* DMITRY LOPAEV, SERGEY ZIRYANOV, NIKOLAY POPOV, *Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics* At the increased pressure the associative ionization is the main ionization mechanism in nitrogen plasma realizing due to reactions of metastable molecules $N_2(A^3\Sigma_u^+)$ and energy stored on high vibrational levels of the ground N_2 molecule state. While the role of these species is relatively well understood, the role of nitrogen atoms both in the ground and excited metastable states is not studied yet in detail. This work just deals with this problem and is focused on studying nitrogen atoms kinetics in DC glow discharge at increased pressures (5-50 Torr). Despite of the low dissociation degree the absolute concentration of nitrogen atoms is quite enough for the influence on the ionization mechanism through fast associative ionization reactions between metastable $N(^2P)$ atoms. The production of nitrogen atoms similarly to $N_2(A^3\Sigma_u^+)$ molecules is associated with the excitation degree of nitrogen vibrations. Thus energy stored in N_2 vibrations can be realized into the stepwise ionization through exciting $N_2(A^3\Sigma_u^+)$ and $N(^2P)$.

*student

[†]student

16:30

FT1 5 Temporal evolution of OH density and gas temperature of nanosecond repetitively pulsed discharges in water vapor at atmospheric pressure FLORENT SAINCT, DEANNA LACOSTE, CHRISTOPHE LAUX, *Ecole Centrale Paris, EM2C Laboratory, France* MICHAEL J. KIRKPATRICK, EMMANUEL ODIC, *Supelec, France* We present a study of plasma discharges produced by nanosecond repetitively pulses in water vapor at 450 K and 1 atm. The plasma was generated in water vapor with 20-ns duration high-voltage (0-20 kV) pulses, at a repetition frequency of 10 kHz, in the spark regime (2 mJ/pulse). To investigate plasma kinetics we focused on intermediate products of the discharge, in particular the hydroxyl radical. Between two discharges, the time-resolved density of OH was measured by Planar Laser Induced Fluorescence (OH-PLIF). The temperature during the discharge was determined by optical emission spectroscopy, and between two pulses by two-color OH-PLIF. A 150 K preheating effect from the previous pulses is measured, with a maximum temperature elevation of 950 K during the first 10 μs following each pulse. The OH density measurements were compared with chemical kinetics simulations. The numerical results obtained with an initial OH density of 500 ppm show good agreement with the experimental data, thus providing a quantification of the OH density produced by the pulse. The electron number density is also measured via stark broadened H_β lines. A kinetics model is proposed to interpret the measures.

16:45

FT1 6 The electron energy distribution of microscale field emission-driven Townsend discharges* YINGJIE LI, DAVID GO, *University of Notre Dame* Attracted by the wide application potential of plasma-surface interactions, this work attempts to better understand the electron energy distribution (EED) of the free electrons in the discharge, which is critical in deciding the most favored type of electron-driven reaction. Particle-in-cell/Monte Carlo collision simulations are applied to study microscale Townsend discharges that can be formed in electrode gaps below 10 μm. Results show that the EED becomes non-continuous in this regime, generating several discrete peaks corresponding to specific inelastic collisions. The existence of these discrete peaks indicates that it is possible to enhance or eliminate certain types of reactions by manipulating the EED. The relative magnitude of these peaks and shape of the energy distribution can be controlled by both pd and the applied potential. pd dictates the number of inelastic collisions experienced by the emitted electrons, and the applied potential dictates the absolute maximum energy of the distribution. As shown in this work, at microscale dimensions, it is possible to control the energy distribution of free electrons to target specific, energy dependent gas-phase or surface reactions.

17:00

FT1 7 Excited states and radicals formations in nanosecond pulse discharge and their evolution in afterglow IVAN SHKURENKOV, DAVID BURNETTE, WALTER LEMPERT, IGOR ADAMOVICH, *The Ohio State University* The results of nanosecond pulse discharge and afterglow simulations carried out with developed one-dimensional self-consistent model in N_2/O_2 and $H_2/N_2/O_2$ gas mixtures and comparison with experimental data are presented. Excited states and radicals formations in the discharge as well as mechanisms of the NO formation and destruction

are discussed. It was shown that NO is rapidly formed in the reaction between excited nitrogen N_2* (both triplet and singlet states) and atomic oxygen in afterglow and is destroyed by atomic nitrogen (reverse Zel'dovich mechanism).

17:15

FT1 8 Vibrational kinetics in a Cl_2 inductively-coupled plasma* BENJAMIN PRUVOST, JEAN-PAUL BOOTH, MICKAEL FOUCHER, PASCAL CHABERT, *LPP-CNRS* VASCO GUERRA, *IST, Lisbon* ILYA FABRIKANT, *U. Nebraska* MARK KUSHNER, *U. Michigan* Inductively-coupled plasmas containing chlorine are widely used for conductor-etch applications, often using mixtures with HBr and O_2. We are carrying out an extensive comparison of experimental measurements with simulations using the Hybrid Plasma Equipment Model (HPEM). Vibrationally excited states of chlorine have historically been ignored in models, but recently we found that inclusion of a simple vibrational kinetic scheme in HPEM significantly improves the model agreement with experiment. Here we will present a more complete scheme, using calculated state-to-state cross-sections (up to v=5) for electron impact excitation and state-specific V-T (Cl_2-Cl_2 and Cl_2-Cl) and V-V (Cl_2-Cl_2) transfer rates. Initially the scheme has been implemented in a global model, which predicts vibrational temperatures up to 2500K at low pressure (3mTorr), dropping to ~700K at 50 mTorr. We are attempting to measure the vibrational distribution using broadband ultraviolet absorption spectroscopy. Vibrationally excited states play a key role in gas heating, as well as significantly enhancing electron attachment, and should not be ignored.

SESSION FT2: HIGH PRESSURE DISCHARGES: DIELECTRIC BARRIER DISCHARGES, CORONAS, BREAKDOWN, SPARKS II
Tuesday Afternoon, 1 October 2013
Room: Ballroom II at 15:30
Ann Bourdon, Laboratoire EM2C, presiding

Contributed Papers

15:30

FT2 1 Plasma chemistry in CO_2 dielectric barrier discharges F. BREHMER, S. WELZEL, *Eindhoven University of Technology, Eindhoven, The Netherlands* M.C.M. VAN DE SANDEN, *Dutch Institute for Fundamental Energy Research (DIFFER), Nieuwegein, The Netherlands* R. ENGELN, *Eindhoven University of Technology, Eindhoven, The Netherlands* Plasma-assisted gas phase conversion in non-thermal environments is increasingly being considered as promising technology for fuel production from CO_2 and hydrogen containing sources. Particularly the rate-limiting activation of CO_2 is suggested to be tackled in plasmas at (sub-)atmospheric pressure conditions without the admixture of carrier gases. Therefore CO_2 dielectric barrier discharges were studied to assess conversion yields and reaction mechanisms. The CO_2 discharges were resonantly excited at around 100 kHz in a flow-tube lab-scale reactor designed to facilitate time-resolved in-situ optical emission and infrared laser absorption spectroscopy. Complementary analysis of the gas phase constituents using ex-situ FT-IR spectroscopy and

a thorough electrical characterisation were carried out. The CO conversion yields were typically below 5% and hence in-line with similar studies. The energy efficiency can be uniformly described for different external plasma parameters (e.g. flow rate, power input, excitation frequency) as function of the specific energy input. Special attention was paid to the non-negligible formation of by-products such as O_3 and O_2 which suggests an inefficient recycling of atomic oxygen in secondary CO_2 dissociation reactions.

15:45

FT2 2 Study and Control of Various Corona Modes in an Atmospheric Pressure Weakly Ionized Plasma Reactor Using a Current Sensor Characterized by a Broad Frequency Band ROKIBUL ISLAM, PATRICK PEDROW, WILLIAM LEKOBOU, KARL ENGLUND, *Washington State University* A broad band current sensor is being used to monitor the various phenomena (primary streamers, secondary streamers, back corona, etc.) associated with an atmospheric pressure needle-array-to-grounded-screen corona discharge. The reactor consists of a PVC tube and the needle array consists of nickel coated steel electrodes with radius of curvature about 50 μm. The grounded screen is made from stainless steel mesh and applied voltage has a frequency of 60 Hz with an RMS value ranging from 0 to 10 kV. The voltage sensor is a resistive divider and the current sensor is a viewing resistor with value 50 Ω. The feed gas stream is presently (argon + acetylene) or (argon + oxygen) with the argon acting as carrier gas and the acetylene and oxygen acting as precursor gases. Voltage and current are captured with a LeCroy 9350AL 500MHz oscilloscope and analyzed with Matlab using digital signal processing algorithms. The goals of the research are 1) to measure reactor electrical power on a real time basis; 2) to provide real time control of the applied voltage and thus avoid spark conditions; and 3) to identify the various corona modes present in the reactor. Processing of substrates takes place downstream from the grounded screen, outside of the harsh corona discharge environment.

16:00

FT2 3 Simulating the inception of pulsed discharges near positive electrodes* JANNIS TEUNISSEN, *Centrum Wiskunde & Informatica* UTE EBERT, *Eindhoven University of Technology* With 3D particle simulations we study the inception of pulsed discharges near positive electrodes. In different geometries, we first determine the breakdown voltage. Then we study the probability of inception for a fast voltage pulse. This probability mostly depends on the availability of seed electrons to generate the initial electron avalanches. These results are compared with experimental observations. Then we investigate how the shape of a starting discharge affects its further development. In particular, we discuss the formation of so-called "inception clouds."

16:15

FT2 4 Investigation of positive streamers by double pulse experiments* SANDER NIJDAM, *Eindhoven University of Technology, The Netherlands* EIICHI TAKAHASHI, *National Institute of Advanced Industrial Science and Technology (AIST), Japan* ARAM H. MARKOSYAN, UTE EBERT, *Centrum Wiskunde and Informatica, Amsterdam* Streamer discharges are influenced by background ionization and other effects of previous discharges. We have studied the influence of repeating positive streamer discharges by applying two subsequent high voltage pulses with a variable interval (200 ns to 40 ms) between them. The discharges are studied with two ICCD cameras that image the discharge during either the

first or the second voltage pulse. Experiments have been performed in a 103 mm point-plane gap at a pressure of 133 mbar in artificial air, pure nitrogen and pure argon. We have found a range of phenomena that depend on the inter-pulse time Δt. For small Δt, (below 1 μs for air and nitrogen and below 15 μs for argon) the streamers just continue their old paths. At larger Δt the conductivity has decreased too much for such continuation. However, parts of the old paths do glow up again like secondary streamers. At still larger Δt (roughly above 2.5 μs for air and 30 μs for nitrogen) new channels appear. At first they avoid the entire area of the previous discharge; next they follow the edges of the old channels; then they start to follow the old channels exactly and finally ($\Delta t > 1$ ms) they become fully independent of the old paths.

16:30
FT2 5 Electric field of atmospheric pressure plasma jet impinging upon a surface and electrical properties of the jet source ANA SOBOTA, OLIVIER GUAITELLA, *LPP, Ecole Polytechnique* ENRIC GARCIA CAUREL, *LPICM, Ecole Polytechnique* ANTOINE ROUSSEAU, *LPP, Ecole Polytechnique* We report on experimentally obtained values of the electric field magnitude of an atmospheric pressure plasma jet impinging upon a dielectric surface. The results were obtained using Pockels technique, on a BSO crystal. The electric field is a function of the gas flow and the area over which the discharge spreads on the dielectric surface. A coaxial configuration of the plasma jet was used, driven by 30 kHz sine voltage, in He flowing at 100-900 SCCM. In this geometry we found 2 modes of operation, a low-power mode stable at one plasma bullet emitted per period and the unstable high-power mode featuring additional micro-discharges. In addition to the electric field measured in the low-power mode, electrical characterization of the jet source will be presented, together with the manner in which properties of the setup can influence the jet and vice versa. The distinction will be made between the plasma jet in room atmosphere and the plasma jet interacting with a dielectric surface.

16:45
FT2 6 Discharge inception in atmospheric air above the breakdown field ANBANG SUN, JANNIS TEUNISSEN, *Centrum Wiskunde & Informatica* UTE EBERT, *Centrum Wiskunde & Informatica; Eindhoven University of Technology* MULTISCALE DYNAMICS TEAM   Streamers play an important role in creating the path of lightning and sprites. They also have wide applications in industry. In this work, we use a 3D particle code to investigate streamer formation in atmospheric air, in a homogeneous electric field above the breakdown threshold. We include the effect of natural background ionization and of photoionization. We see that numerous avalanches start from different locations, these avalanches overlap and screen the electric field in the interior of discharges. Finally, no isolated streamer forms in this region. We give an analytical estimation of the screening ionization time which is a generalization of the Maxwell relaxation time in ionizable media. Our results are very different from so-called double-headed streamers that were found in previous fluid models. Our simulations are in agreement with recent experimental observations. [A. Sun *et al.*, Geophys. Res. Lett., **40**, 1-6 (2013)].

SESSION FT3: LIQUIDS II
Tuesday Afternoon, 1 October 2013; Room: Nassau Room at 15:30; Andrey Starikovskiy, Princeton University, presiding

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Invited Papers

15:30
FT3 1 Atmospheric Pressure Glow Discharge with Liquid Electrode* FUMIYOSHI TOCHIKUBO, *Tokyo Metropolitan University*

Nonthermal atmospheric pressure plasmas in contact with liquid are widely studied aiming variety of plasma applications. DC glow discharge with liquid electrode is an easy method to obtain simple and stable plasma-liquid interface. When we focus attention on liquid-phase reaction, the discharge system is considered as electrolysis with plasma electrode. The plasma electrode will supply electrons and positive ions to the liquid surface in a different way from the conventional metal electrode. However, the phenomena at plasma-liquid interface have not been understood well. In this work, we studied physical and chemical effect in liquid induced by dc atmospheric pressure glow discharge with liquid electrode. The experiment was carried out using H-shaped Hoffman electrolysis apparatus filled with electrolyte, to separate the anodic and cathodic reactions. Two nozzle electrodes made of stainless steel are set about 2 mm above the liquid surface. By applying a dc voltage between the nozzle electrodes, dc glow discharges as plasma electrodes are generated in contact with liquid [1]. As electrolyte, we used aqueous solutions of NaCl, Na_2SO_4, $AgNO_3$ and $HAuCl_4$. $AgNO_3$ and $HAuCl_4$ are to discuss the reduction process of metal ions for synthesis of nanoparticles (NPs). OH radical generation yield in liquid was measured by chemical probe method using terephthalic acid. Discharge-induced liquid flow was visualized by Schlieren method. Electron irradiation to liquid surface (plasma cathode) generated OH^- and OH radical in liquid while positive ion irradiation (plasma anode) generated H^+ and OH radical. The generation efficiency of OH radical was better with plasma anode. Both Ag NPs in $AgNO_3$ and Au NPs in $HAuCl_4$ were synthesized with plasma cathode while only Au NPs were generated with plasma anode. Possible reaction process is qualitatively discussed. The discharge-induced liquid flow such as convection pattern was strongly influenced by the gas flow on the liquid surface.

[1]N. Shirai *et al.*, Plasma Sources Sci. Technol. 20 (2011) 034013.

Contributed Papers

16:00

FT3 2 Plasma processes in water under effect of short duration pulse discharges ELCHIN GURBANOV, *moslem* It is very important to get a clear water without any impurities and bacteria by methods, that don't change the physical and chemical indicators of water now. In this article the plasma processes during the water treatment by strong electric fields and short duration pulse discharges are considered. The crown discharge around an electrode with a small radius of curvature consists of plasma leader channels with a high conductivity, where the thermo ionization processes and UV-radiation are taken place. Simultaneously the partial discharges around potential electrode lead to formation of atomic oxygen and ozone. The spark discharge arises, when plasma leader channels cross the all interelectrode gap, where the temperature and pressure are strongly grown. As a result the shock waves and dispersing liquid streams in all discharge gap are formed. The plasma channels extend, pressure inside it becomes less than hydrostatic one and the collapse and UV-radiation processes are started. The considered physical processes can be successfully used as a basis for development of pilot-industrial installations for conditioning of drinking water and to disinfecting of sewage.

16:15
FT3 3 ABSTRACT WITHDRAWN

16:30

FT3 4 Investigation of OH Radical Generation Rate in Liquid induced by Non-equilibrium Atmospheric Pressure Plasma Jet Irradiation* TATSUO ISHIJIMA, YUKO IMAZAWA, KAZUAKI NINOMIYA, KENJI TAKAHASHI, YASUNORI TANAKA, YOSHIHIKO UESUGI, *Kanazawa University* Non-equilibrium atmospheric pressure plasma jet (NAPPJ) is one of the convenient tools to supply reactive species to liquid under atmospheric pressure condition. Since a wide range of excitation frequencies is used to produce NAPPJs such as DC to microwave, it is necessary to obtain quantitative estimates of reactive species generation rate in liquid when the NAPPJ is irradiate to liquid surface. We have investigated hydroxyl radicals (OH) generation rate in liquid as one of a fundamental reactions using a chemical dosimetry technique based on a terephthalic acid (TA) when a pulsed 2.45 GHz microwave plasma jet (MWPJ) and low frequency ($\sim$20 kHz) plasma jet (LFPJ) source were used. Both MWPJ and LFPJ were produced at a He gas flow rate of less than 8 slm into a quartz tube. In order to evaluate the applicability of TA technique, the irradiation distance between the quartz nozzle edge and liquid surface was carefully investigated, taking into account linear dependence on irradiation time. As a result, we have found that OH generation rate of MWPJ was about 3 times lower than that of LFPJ in present operating conditions.

16:45

FT3 5 Fabrication of hybrid nanostructures by liquid plasma for biomedical applications* SRI BALAJI PONRAJ, XIUJUAN JANE DAI, LUHUA LI, ZHIQIANG CHEN, JAYANTH SURYA NARAYANAN, JAGAT KANWAR, *Deakin University* JOHAN DU PLESSIS, *RMIT University* Liquid plasma, generated by a nanosecond pulsed generator at atmospheric pressure, was used to treat bamboo-like boron nitride nanotubes (BNNTs). It was ob-served that the length of the BNNTs was reduced and found more cup like structures called boron nitride nanocups (BNNCs). Interestingly, a new peak appeared at 406.86 eV in the N1s X-ray photoelectron spectrum, which seems to be attributable to the oxidation of nitrogen (N-O) in BNNTs. The C1s spectrum showed that oxygen functional groups were introduced onto the BNNT/BNNC surface. The liquid plasma was also used to assemble gold nanoparticles onto the treated BNNTs/BNNCs. This hybrid nanostructure was fabricated efficiently, compared with normal equilibrium conditions. The pH values and conductivity of all samples were measured. After plasma treatment, the pH values were greatly reduced and conductivity was significantly increased. We propose that the plasma acid, hydrogen peroxide, OH$^-$, H ions and radicals formed in liquid plasma as well as the pulsed electric field contribute to the oxidation of nitrogen, reduced length of the BNNTs(forming BNNCs), surface functionalization, and to the fabrication of hybrid nanostructure. The cytotoxic tests for these hybrid nanostructures is underway.

17:00

FT3 6 Plasma electrolysis using atmospheric dc glow discharge in contact with liquid for synthesis of metal nanoparticles* NAOKI SHIRAI, YUDAI SHIMOKAWA, TAKUYA AOKI, SATOSHI UCHIDA, FUMIYOSHI TOCHIKUBO, *Tokyo Metropolitan University* For the synthesis of metal nanoparticles in aqueous solution, we propose dual plasma electrolysis, which consists of Hoffman electrolysis apparatus with two atmospheric glow discharge plasmas as electrodes instead of conventional metal electrodes immersed in a liquid. The plasma anode irradiates positive ions to the solution surface while the plasma cathode irradiates electrons to the solution surface. The dual plasma electrolysis system enables us simultaneously to investigate the influence of electron and positive ion irradiation to a solution surface on metal nanoparticle generation at the same current. We used aqueous solutions of AgNO$_3$, HAuCl$_4$ and their mixture. In dual plasma electrolysis with AgNO$_3$, Ag nanoparticles were only synthesized on the plasma cathode side. This means that Ag nanoparticles are generated via the reduction of Ag$^+$ by electrons. With HAuCl$_4$ solution, Au nanoparticles were synthesized on both the plasma anode and plasma cathode sides. Ion irradiation with the plasma anode is more effective than electron irradiation for Au nanoparticle synthesis. This finding suggests that positive ions from the plasma trigger the dissociative reaction of AuCl$_4^-$ at the plasma-liquid interface.

17:15

FT3 7 On The Possibility of Preferential Reactions at Plasma-Liquid Interface Due To Electric Double Layer* TATSURU SHIRAFUJI, *Osaka City University* FUMIYOSHI TOCHIKUBO, *Tokyo Metropolitan University* Plasmas in and in contact with liquid have attracted much attention because of their possible application fields such as nano materials synthesis, surface modification, water treatment, sterilization, recycling of rare materials, and decomposition of toxic compounds. The most important part in the plasmas in contact with liquid is the interface between the gas-phase plasma and liquid. According to electrochemistry, a nano-scale electric double layer (EDL) is formed on the top surface of the liquid. Thus,

in a plasma treatment of liquid medium, gas-phase active species in the plasma primarily encounter the liquid-phase species in the EDL. For the purpose of precise control of plasmas in contact with liquid, we must pay attention to the formation and behavior of the EDL. In this work, numerical simulation of the EDL in contact with a dielectric barrier discharge has been performed. Preferential appearance of positive or negative ions has been observed on the top surface of the liquid depending on the mass ratio of the positive and negative ions in the liquid, and on the frequency applied. This means that the preferential reactions can be realized between gas-phase plasma species and liquid phase ions.

SESSION GT1: TOUR OF THE PRINCETON PLASMA PHYSICS LABORATORY
Tuesday Evening, 1 October 2013
Room: at 18:00
Andrew Zwicker, Princeton Plasma Physics Laboratory, presiding

Contributed Papers

18:00
GT1 1 Tour of the Princeton Plasma Physics Laboratory AN-DREW ZWICKER, *Princeton Plasma Physics Laboratory*

HW1 1 PLASMA DATA EXCHANGE PROJECT

HW1 2 A Web-based Delphi System for Evaluating Plasma Properties JUN-HYOUNG PARK, MI-YOUNG SONG, *National Fusion Research Institute* Plasma data bases are necessarily required to compute the plasma parameters, high reliable data bases are closely related with accuracy enhancement of simulations. Therefore, in this work, we developed a web-based Delphi system to obtain more accurate plasma properties such as electron-atom and electron-molecule collision cross sections. The Delphi method is a well-known structured communication technique which relies on a panel of experts. In principle, forecasts or decisions from a structured group of individuals are more accurate than those from unstructured groups. In our system, a number of plasma property experts can evaluate the plasma data using web sites that allow the process to be conducted in real-time.

HW1 3 Consistent set of electron cross sections for methane* L.L. ALVES, V. GUERRA, *IPFN/IST-UTL, Portugal* C.D. PINTASSILGO, *IPFN/FEUP, Portugal* This contribution presents a complete consistent set of electron-impact cross sections for methane (CH_4), recently made available on the IST-LISBON database with the LXCat website [1]. The set is based on the cross sections originally compiled and adjusted in [2] and first used in [3]. The elementary processes taken into account are elastic momentum-transfer, vibrational excitation of the (1,3) and (2,4) modes, total dissociation into neutrals, and ionization producing CH_4^+ and CH_3^++H. For the latter two processes we have adjusted the partial ionization cross section of Chatham *et al.* [4] as to reproduce their measured total ionization. The new cross-section set is validated by comparing calculated and measured electron swarm parameters for $E/N = 0.1$–400 Td. A discussion of similarities and differences with sets of CH_4 cross sections from other databases is also presented.

[1]http://www.lxcat.laplace.univ-tlse.fr/
[2]C. D. Pintassilgo, Master Thesis, Instituto Superior Técnico (Universidade Técnica de Lisboa), 1996.
[3]C. D. Pintassilgo *et al.*, Plasma Sources Sci. Technol. **8**, 463 (1999).
[4]H. Chatham *et al.*, J. Chem. Phys. **81**, 1770 (1984).

HW1 4 Updating the IST-LISBON electron cross sections for nitrogen* L.L. ALVES, L. SOMBREIREIRO, P. VIEGAS, V. GUERRA, *IPFN/IST-UTL* In this work we update the complete and consistent set of nitrogen (N_2) electron-impact cross-section with the IST-LISBON database, available on the LXCat website [1]. The update has extended, in energy scale up to 1 keV, the cross sections for effective momentum-transfer, excitation to electronic states and ionization. The set further accounts for excitation to rotational and vibrational excited states. Calculations using BOLSIG+ [2] with the new cross sections give swarm parameters in very good agreement with available experimental data for the reduced mobility, the characteristic energy and the reduced ionization coefficient, for a very extended E/N range up to 1000 Td. The influence of rotational excitations/de-excitations at low E/N and different rotational temperatures is discussed. A critical evaluation of similarities and differences with sets of N_2 cross sections from other databases is carried out. Moreover, the procedure to de-convolute global cross sections into state-to-state vibrational level dependent cross sections is outlined and discussed.

[1]http://www.lxcat.laplace.univ-tlse.fr/
[2]G. J. M. Hagelaar and L. C. Pitchford, Plasma Sources Sci. Technol. **14**, 722 (2005).

HW1 5 Pressing data needs for plasma-water interaction studies BILL GRAHAM, *Queens University Belfast, UK* PETER BRUGGEMAN, *University of Minnesota, USA* MARK KUSHNER, *University of Michigan, USA* ZORAN PETROVIC, *Institute of Physics, Belgrade, Serbia* It is clear that there is a growing scientific and technological interest in the physics and chemistry of plasmas created in contact with or in the presence of water vapor. This requires knowledge of the cross sections or rate coefficients for a vast number of collision processes and there are some invaluable reviews of the available data [1], however much more data is needed. Our personal views on the most pressing needs will be presented but here are our top 5. (1) An electron impact cross section set for OH that is as extensive as that available for H_2O. (2) The rates for heavy particle reactions with vibrationally excited $H_2O(v)$ and $OH(v)$ (3) The cross sections/rate coefficients for reactions involved in positive and negative ion water clustering. (4) The temperature dependence of three body reactions. (5) The reactions at and yields from the plasma-liquid water surface interface, and their rates. In addition we need to be able to determine rates for collisions and reactions in liquid water.

[1]Y. Itikawa and N. Mason, J. Phys. Chem Ref Data. **34**, 1 (2005).

HW1 6 Evaluation of theoretical cross sections for electron scattering from noble gases for plasma modeling* LEANNE PITCHFORD, *CNRS and Univ Toulouse* O. ZATSARINNY, K. BARTSCHAT, *Drake Univ, USA* D.V. FURSA, I. BRAY, *Curtin Univ, Australia* L.L. ALVES, *IPFN/IST-UTL, Portugal* S. BIAGI, *Univ Liverpool, United Kingdom* Can state-of-the-art theory now provide *complete* sets of cross sections for electron scattering from noble gases suitable for use in Boltzmann calculations of swarm parameters and to the accuracy required for plasma modeling? The answer is a qualified "yes" for He, Ne, and Ar, but "not yet" for Kr and Xe. Purely theoretical cross section sets for electron scattering from these species are presently available on the LXCat website in the BRAY database for He (calculated using the convergent close-coupling technique, formulated in momentum space) and in the BSR database for the other rare gases (obtained with a convergent B-spline R-matrix with pseudo-states method, formulated in coordinated space). Although significant differences occasionally appear in some of the cross sections between experiment and theory, the calculated ionization rate coefficients as a function of reduced electric field strength, E/N, for He, Ne and Ar agree with experiment to within a few percent for the three lighter noble gases.

HW1 7 ATOMIC AND MOLECULAR PROCESSES

HW1 8 Objects curvature at movement AYMAN KAMEL, *National Research Center* By simple experiment and notice its results, the objects curvature relativity to observer's measurements and that happened at movement the objects to others. By using Lorentz's transformations and modified it according to the experiment had done, the results prove that objects move in straight direction but in curve pathway. The results were proving that there are two sorts of curvature, the first is "relative curvature" and the second is "self-curvature." According to two before hypothesis which the first is "relative curvature" and the second is "self-curvature" that depends on first assume, discovered new character has to all movement objects regardless of the observer's measurements.

HW1 9 Dynamic shielding effect on the polarization momentum transport collision in strongly coupled semiclassical plasmas YOUNG-DAE JUNG, *Hanyang University, Ansan* The influence of the quantum dynamic shielding on the polarization momentum transport collision is investigated in strongly coupled semiclassical plasmas. The electron-atom polarization momentum transport cross section is obtained by the Faxen-Holtzmark theory as a function of the collision energy, de Broglie wavelength, Debye length, thermal energy, and atomic quantum states. It is found that the dynamic shielding effect enhances the scattering phase shift as well as the polarization momentum transport cross section. The variation of quantum effect on the momentum transport collision due to the change of thermal energy and de Broglie wavelength is also discussed.

HW1 10 IAEA activities on atomic, molecular and plasma-material interaction data for fusion BASTIAAN J. BRAAMS, HYUN-KYUNG CHUNG, *Nuclear Data Section, International Atomic Energy Agency* The IAEA Atomic and Molecular Data Unit (http://www-amdis.iaea.org/) aims to provide internationally evaluated and recommended data for atomic, molecular and plasma-material interaction (A+M+PMI) processes in fusion research. The Unit organizes technical meetings and coordinates an A+M Data Centre Network (DCN) and a Code Centre Network (CCN). In addition the Unit organizes Coordinated Research Projects (CRPs), for which the objectives are mixed between development of new data and evaluation and recommendation of existing data. In the area of A+M data we are placing new emphasis in our meeting schedule on data evaluation and especially on uncertainties in calculated cross section data and the propagation of uncertainties through structure data and fundamental cross sections to effective rate coefficients. Following a recent meeting of the CCN it is intended to use electron scattering on Be, Ne and N2 as exemplars for study of uncertainties and uncertainty propagation in calculated data; this will be discussed further at the presentation. Please see http://www-amdis.iaea.org/CRP/ for more on our active and planned CRPs, which are concerned with atomic processes in core and edge plasma and with plasma interaction with beryllium-based surfaces and with irradiated tungsten.

HW1 11 ELECTRON AND PHOTON COLLISIONS WITH ATOMS AND MOLECULES: EXCITATION

HW1 12 Photon's Wavelength Stretching and Shrinking? FLORENTIN SMARANDACHE, *University of New Mexico* The photon is considered of having a dual form: wave and particle. (a) If the photon is a wave, it has been asserted that the photon's wavelength is stretched inside the intergalactic space, because of the expansion of the universe. But what happens with the photon's wavelength when the photon enters a galactic space (which is not expanding), and afterwards it exists the galactic space and enters an intergalactic space (which is expanding), and so on? But, when the wavelength increases the wave frequency decreases (redshift); therefore the wave's momentum and energy are diminished in the expansion of the universe. It seems to be an antithesis between the quantum mechanics (Copenhagen style) and the universe expansion. (b) If the photon is a particle, similarly because of the so-called expansion of the universe, does its pathlength increases inside the intergalactic space (which is expanding) and decreases inside the galactic space (which is not expanding)? Thus, what happens with its pathlength when the photon passes from an intergalactic space to a galactic space, then again to intergalactic space, and so on?

HW1 13 Electron Collision Radiative Parameters for O^{2+}* SWARAJ TAYAL, *Clark Atlanta University* The improved radiative and collision atomic parameters calculations for O^{2+} have been performed using the B-spline Breit-Pauli R-matrix method. The flexible non-orthogonal sets of spectroscopic and correlation radial functions are employed for an accurate representation of the target states and scattering functions. The close-coupling expansion includes 126 bound levels covering all possible terms of the ground $2s^2 2p^2$ and excited $2s 2p^3$, $2p^4$, $2s^2 2p3s$, $2s^2 2p3p$, $2s^2 2p3d$, $2s 2p^2 3s$, $2s^2 2p4s$, $2s^2 2p4p$, $2s 2p^2 3p$, $2s 2p^2 3d$, $2p^3 3s$, $2p^3 3p$, and $2p^3 3d$ configurations. The calculated excitation energies of the target levels are in excellent agreement with experiment and represent an improvement over the previous calculations. The present results of cross sections are compared with a variety of other close-coupling and distorted-wave calculations. The oscillator strengths and transition probabilities are in good agreement with other theories and available experimental data. The present cross sections are in good agreement with other theories for many transitions.

HW1 14 Nonperturbative electron-ion scattering theory incorporating the Møller interaction* CHRISTOPHER J. BOSTOCK, DMITRY V. FURSA, IGOR BRAY, *Curtin University* Relativistic distorted wave studies by Fontes's *et al.* [Phys. Rev. A **47**, 1009 (1993)] demonstrated that the Generalized Breit interaction (equivalently the Møller interaction) can affect electron-impact excitation cross sections of hydrogenlike U^{91+} by more that 50% in comparison to calculations that employ the Coulomb interaction alone. We present the first calculations that investigate the effects of both the Møller interaction and close-coupling in the calculation of

electron-impact excitation cross sections [1]. Electron scattering from U^{91+} is used as a test case. The RCCC method is nonperturbative and we emphasise the restrictions and subsequent limitations associated with employing the Møller interaction in the RCCC method.

[1]C. J. Bostock, D. V. Fursa, and I. Bray, Phys. Rev. A **86**, 042709 (2012).

HW1 15 Photoionization of Phosphorus cation induced by synchrotron radiation ANTONIO JUÁREZ, *Universidad Nacional Autónoma de México, A. P. 48-3, Cuernavaca 62251, México* ALEJANDRO AGUILAR, *The Advanced Light Source, Lawrence Berkeley National Laboratory, CA 94720, USA* OLMO GONZÁLEZ, *University of Groningen, 9747 AA Groningen, The Netherlands* DAVID MACALUSO, *Physics Department, Montana State University, Montana 59717, USA* ARMANDO ANTILLÓN, ALEJANDRO MORALES, *Universidad Nacional Autónoma de México, A. P. 48-3, Cuernavaca 62251, México* DAG HANSTORP, *University of Gothenburg, SE-412 96 Gothenburg, Sweden* AARON COVINGTON, KIATTICHART CHARTKUNCHAND, *Physics Department, University of Nevada Reno, NV 89557-0220* GUILLERMO HINOJOSA, *Universidad Nacional Autónoma de México, A. P. 48-3, Cuernavaca 62251, México* SULTANA NAHAR, *The Ohio State University, OH 43210-1173* EDGAR HERNÁNDEZ, *Universidad Autónoma del Estado de Morelos, Cuernavaca 62210, México* The photoionization of Phosphorus cation has been measured in the photon energy range of 18 eV to 50 eV with 40 meV resolution. A theoretical investigation is being conducted while more experimentation is being planned.

HW1 16 Photoionization of Cl II induced by synchrotron radiation ANTONIO JUÁREZ, *Universidad Nacional Autónoma de México, A.P. 48-3, Cuernavaca 62251, México* ALEJANDRO AGUILAR, *The Advanced Light Source, Lawrence Berkeley National Laboratory, CA 94720, USA* OLMO GONZÁLEZ, *University of Groningen, 9747 AA Groningen, The Netherlands* DAVID MACALUSO, *Montana State University, Bozeman, Montana 59717, USA* ARMANDO ANTILLÓN, ALEJANDRO MORALES, *Universidad Nacional Autónoma de México, A.P. 48-3, Cuernavaca 62251, México* DAG HANSTORP, *University of Gothenburg, SE-412 96 Gothenburg, Sweden* EDGAR HERNÁNDEZ, *Universidad Autónoma del Estado de Morelos, Cuernavaca 62210, México* GUILLERMO HINOJOSA, *Universidad Nacional Autónoma de México, A.P. 48-3, Cuernavaca 62251, México* The photoionization of Chlorine ions is a fundamental process of interest in several plasma environments. For instance, in FC reactors, negative halogen ions beams are candidates for the injectors. In astrophysics Cl was detected in Io's ionosphere and is used as hydrogen abundance markers. The photoionization of Cl^+ was measured with a resolution of 20 meV in the photon energy range of 19.5 eV to 27.5 eV. The experiment was carried out in the 10.0.1 end station of the Advanced Light Source. Structures corresponding to Rydberg series are identified. Absolute cross sections were measured.

HW1 17 ELECTRON AND PHOTON COLLISIONS WITH ATOMS AND MOLECULES: IONIZATION

HW1 18 Electron impact total cross sections for Furan, Tetrahedrofuran and 2, 5-Dimethylefuran (0.1 eV – 5000 eV)* CHETAN LIMBACHIYA, *P.S. Science & H.D. Patel Arts College, KADI* MINAXI VINODKUMAR, *V.P. & R.P.T.P. Science College, Vallabh Vidyanagar* MOHIT SWADIA, *P.S. Science & H.D. Patel Arts College, KADI* Furan may serve as a prototype of a furanose-form building unit of biomolecules [1]. Electron interactions with tetrahydrofuran (THF), that links the phosphate groups in the DNA backbone, have been studied by both experimental and computational methods [2]. We have calculated various total cross sections for electron interactions with Furan, Tetrahedrofuran and an industrially relevant molecule 2, 5 – Dimethylefuran. We have used R-matrix code [3] below 15 eV and Spherical Complex optical Potential (SCOP) and Complex Scattering Potential – ionization contribution (CSP-ic) formalisms [4] beyond 15 eV.

[1]Szmytkowski *et al.*, Phys. Rev. A **82**, 032701 (2010).
[2]Khakoo *et al.*, Phys. Rev. A **85**, 052717 (2012).
[3]Bouchiha *et al.*, J. Phys. B: At. Mol. Opt. Phys. **40**, 1259 (2007).
[4]Chetan Limbachiya *et al.*, Phys. Rev. A **83**, 042708 (2011).

HW1 19 Deep minimum in the Coulomb-Born TDCS for inner-shell ionization of carbon by electron impact* S.J. WARD, *University of North Texas* J.H. MACEK, *University of Tennessee* Recently, a minimum in the TDCS of electron impact ionization of helium has been explained in terms of a vortex [1]. We have determined the kinematics to obtain a deep minimum due to a vortex in the TDCS for K shell ionization of carbon by electron impact using the Coulomb-Born (CB1) approximation [3]. The deep minimum occurs at an angle of the ejected electron of 239° for an incident energy of $1801.2eV$, a scattering angle of 4°, and energy of the ejected electron of $5.5eV$. At the angle of the minimum, both the real and imaginary parts of the T-matrix are zero. The integral of the velocity field around a closed path encircling the vortex position is 2π [2]. Following the treatment of Ref. [3], we decomposed both the Born (B1) and the CB1 T-matrix into their multipole components [4]. The $\ell = 1$, $m = \pm 1$ CB1 multipole components are important in determining the shape of the CB1 angular distribution.

[1]J. H. Macek, J. B. Sternberg, S. Y. Ovchinnikov, and J. S. Briggs, Phys. Rev. Lett. **104**, 033201 (2010).
[2]S. J. Ward and J.H. Macek, http://meetings.aps.org/link/BAPS.2011.DAMOP.Q1.63.
[3]J. Botero and J. H. Macek, Phys. Rev. A **45**, 154 (1992).
[4]S. J. Ward and J. H. Macek, Bull. Am. Phys. Soc. **58**, no. 6, p. 61 (2013).

HW1 20 Ionization cross sections and rate coefficients for CFCl$_3$ molecule by electron impact SATYENDRA PAL, NEERAJ KUMAR, *Department of Physics, MMH College, Ghaziabad, Uttar Pradesh, India* Chlorofluorocarbons (CFCs) or freons are important industrial material with wide-ranging applications as refrigerant, aerosol propellant and semiconductor etchant, etc. The large-scale industrial consumption is of particular environmental concern because of its potential for ozone destruction in the stratosphere. The present work reports the calculations for differential cross sections as a function of secondary/ ejected electron energy and the scattering angle in the ionization of CFCl$_3$ by electron collision leading to the production of various cations viz. CCl_3^+, $CFCl_2^+$, CCl_2^+, $CFCl^+$, CCl^+, Cl^+, CF^+, F^+, and C^+ through direct and dissociative ionization processes at a fixed incident electron energy of 200 eV. A modified Jain-Khare semi-empirical formalism based on oscillator strength has been employed. To the best of our knowledge, no experimental and/or theoretical data is available for comparison of the present results for differential cross sections. The corresponding derived integral cross sections in terms of the partial ionization cross sections corresponding to these cations, in the energy range varying from ionization threshold to 1000 eV, revealed a reasonably good agreement with the experimental and theoretical data, wherever available. In addition to the differential and integral ionization cross sections, we have also calculated the ionization rate coefficients using the evaluated partial ionization cross sections and the Maxwell-Boltzmann distribution as a function of electron energy.

HW1 21 Electron Impact Ionization cross sections and rate coefficients for α-tetra hydro furfuryl alcohol NEERAJ KUMAR, SATYENDRA PAL, *Department of Physics, MMH College, Ghaziabad, Uttar Pradesh, India* α-tetrahydrofurfuryl alcohol (THFA; $C_5H_{10}O_2$) is an aromatic compound having the molecular structure similar to that of 2-deoxy-D-ribose (deoxyribose). This molecule has attracted enormous interest in the field of research because its electron charge cloud possesses a quite significant spatial extent (dipole polarizability, $\alpha = 70.18$ au) and has a relatively strong permanent dipole moment ($\mu \sim 2$D). In the present work, we have extended and generalized the modified Jain-Khare semi-empirical formalism for the evaluation of the total ionization cross sections corresponding to the formation of the cations in the electron impact ionization of molecules to the electron impact ionization of α-tetrahydrofurfuryl alcohol (THFA; $C_5H_{10}O_2$), in the energy range varying from ionization threshold to 1000 eV. The evaluated cross sections revealed a reasonably good agreement with the experimental and theoretical data, wherever available. We have also calculated the ionization rate coefficients as a function of electron energy, using the evaluated total ionization cross sections and the Maxwell-Boltzmann distribution.

HW1 22 Electron Collisions with Argon at Low and Intermediate Energies* OLEG ZATSARINNY, KLAUS BARTSCHAT, *Drake University* We have further developed the B-Spline R-matrix (BSR) method [1] and the corresponding computer code [2] to allow for a large number of pseudo-states in the close-coupling expansion. In the present work, we carried out semi-relativistic (Breit-Pauli) close-coupling calculations for elastic scattering, excitation, and ionization of argon from both the ground state and the metastable excited states. Coupling to the ionization continuum through the pseudo-states is important for low-energy elastic scattering (to represent polarizability effects), for excitation in the "intermediate" energy regime of about 1-3 times the ionization potential, and to allow for the calculation of ionization processes by transforming the results obtained for excitation of the positive-energy pseudo-states. The current results represent a significant extension of our earlier near-threshold work [3] on the e-Ar collision system. Many of these data are now available in the LXCat database [4].

[1] O. Zatsarinny and K. Bartschat, J. Phys. B **46** (2013) 112001.
[2] O. Zatsarinny, Comp. Phys. Commun. **174** (2006) 273.
[3] O. Zatsarinny and K. Bartschat, J. Phys. B **37** (2004) 4693.
[4] http://www.lxcat.laplace.univ-tlse.fr/database.php

HW1 23 ABSTRACT WITHDRAWN

HW1 24 A new experimental technique for the measurement of absolute electron-impact partial ionization cross sections of radical species* DARRYL JONES, *School of Chemical and Physical Sciences, Flinders University* GEORGE DA SILVA, *Universidade Federal de Mato Grosso* MICHAEL BRUNGER, *CAMS, Flinders University* We describe a new experimental methodology for measuring absolute partial ionization cross sections (PICS). The new technique employs pulsed and crossed electron and skimmed supersonic beams with an orthogonal pulsed-extraction time-of-flight mass spectrometer. Absolute scales for PICS of a species are determined through normalisation to a reference PICS. Here we determine the relative density of the target and the reference gases by normalisation of their centreline intensities in their expansions. Preliminary data demonstrating the validity of this technique will be presented. The potential of this new technique for performing new experimental measurements on transient radical species will be discussed.

HW1 25 Generalized Sturmian Functions approach for double photoionization of He JUAN M. RANDAZZO, *Centro Atomico Bariloche, Argentina* GUSTAVO GASANEO, *Universidad Nacional del Sur, Argentina* LORENZO UGO ANCARANI, *Université de Lorraine, France* FLAVIO D. COLAVECCHIA, *Centro Atomico Bariloche, Argentina* DARIO M. MITNIK, *IAFE, Buenos Aires, Argentina* Various techniques have been developed in the last decade allowing the ab initio treatment of three-body Coulomb problems. One of the most recent ones is the Generalized Sturmian Function (GSF) method that we have developed [1]. This spectral method allows one to correctly describe bound states of a large variety of systems, but more importantly to generate double continuum wave function for break-up processes possessing the correct asymptotic behavior. In the method, the scattering wave function is expanded in a properly symmetrized product of continuum-type, radial, generalized Sturmian basis functions. The proposal is then used to solve the driven equation for a given process. During the last years, we have studied several S-wave collision models which allowed us to understand the way in which the entangled, three–body, continuum wave is constructed. In this contribution, we consider the full three–body Schrödinger equation for the double photoionization of He at intermediate incident energies. We will illustrate the success of the GSF method by comparing our theoretical cross sections (within different gauges) with those obtained with other approaches and with experimental data.

[1] G. Gasaneo *et al.*, submitted to Adv. in Quantum Chem.; Mitnik *et al.*, Comp. Phys. Comm. **182**, 1145 (2011).

HW1 26 Angular distributions for electron-impact ionization of Na and Mg G.S.J. ARMSTRONG, J. COLGAN, *Theoretical Division, Los Alamos National Laboratory* K.L. NIXON, A.J. MURRAY, *University of Manchester* M.S. PINDZOLA, *Department of Physics, Auburn University* We present angular distributions for electron-impact single ionization of sodium and magnesium at intermediate electron impact energies. In this work, the time-dependent close-coupling (TDCC) method is used to solve the two-electron time-dependent Schrödinger equation in full dimensionality. The ionization process is treated as a two-active-electron process, where the two outgoing electrons move in the field of the frozen singly-charged ion. We compare calculated angular distributions with measurements taken over a range of intermediate electron impact energies, and in both coplanar symmetric and asymmetric geometries. Several new features are incorporated into the present TDCC approach, including a core orthogonalization at each time step to avoid unphysical de-excitation of the active electrons, an implicit time propagator, and a variable radial mesh. The latter is required to map out the inner atomic orbitals accurately, and the use of an implicit time propagator enables reasonably large time steps to be used.

HW1 27 BASIC PLASMA PHYSICS PHENOMENA IN LOW-TEMPERATURE PLASMAS

HW1 28 Study of two-stream instability in low-pressure discharge* GUIQIU WANG, *Dalian Maritime University, Princeton Plasma Physics Laboratory* IGOR KAGANOVICH, ALEXANDER KHRABROV, *Princeton Plasma Physics Laboratory* HONGYUE WANG, *Beihang University, Princeton Plasma Physics Laboratory* DMYTRO SYDORENKO, *University of Alberta* Electron emission from discharge chamber wall is important in low-pressure discharges, such as capacitively coupled plasma (CCP), divertor plasmas, direct current cathode discharges, direct current magnetrons, multipactors, electrostatic, Hall thruster and so on. It is well known that the electrons emitted from the wall are accelerated into plasma by the electric field in the sheath adjacent to the wall and form an electron beam. Such beams on the one hand play an important role in the maintenance of discharge and affect plasma and sheath characteristics, on the other hand, they may excite the two-stream instability in the plasma. As a result, the beam electrons are slowed down and the plasma electrons are heated. In this work, a one-dimensional Particle-in-Cell (PIC) simulation is carried out to study these effects in low-pressure discharge. The relationship between Electron velocity distribution function (EVDF) of plasma-beam system and the two-stream instability whether happens is discussed and the dispersion relation is studied in detail when the two-stream instability occurs.

HW1 29 Oscillatory modes of two particulates levitated in an RF plasma AMIT MUKHOPADHYAY, JOHN GOREE, BIN LIU, *The University of Iowa* A dusty plasma contains micron-size particulates of solid matter. The particulates collect more electrons than ions from the plasma and charge to -4000 e. They are electrically levitated by a sheath electric field. We dropped 4.8 μm polymer microspheres into a capacitively coupled 13.56 MHz RF discharge with 13 mTorr Ar. By shaping the sheath above the horizontal electrode, we were able to confine just two particulates so that they were aligned vertically or horizontally. Using high-speed video microscopy as the diagnostic, we observed the random motion of the particulates, which we analyzed to determine their harmonic oscillations and correlations. Langevin simulations of the particulate motion, taking into account Debye shielding modified by the ion wakefield downstream of the particulates, are compared to experiments. Work supported by NASA and NSF.

HW1 30 Driving Azimuthal Modes in Magnetized Discharge with Segmented Anode YUAN SHI, YEVGENY RAITSES, AHMED DIALLO, *Princeton Plasma Physics Laboratory* Coherently rotating azimuthal modes in a magnetized discharge of the cylindrical Hall thruster were driven using segmented anode. Unlike naturally occurring spoke which rotates only in ExB direction with some specific frequency, coherently rotating modes can be driven in both ExB and -ExB directions, whose frequencies exactly follow driving frequencies. To drive these modes, square-wave voltage between 225 V and 275 V was applied onto four anode segments with successive 90° phase shift. The driving circuit was operated at frequencies ranged from 50 KHz to -50 KHz. Modes appeared to be less intense but more coherent in "direct" magnetic configuration compared to "cusp"; and for each magnetic configuration, the degree of coherence showed strong dependence on driving frequency. Driving at frequencies deviate from the spoke frequency suppressed the naturally occurring azimuthal mode, while driving at spoke frequency enhanced the coherence of natural spoke. This resonant behavior was observed by a fast camera as well as current through anode segments.

HW1 31 Emission spectroscopy of anharmonic vibrational series for micro-hollow cathode discharge plasmas* A. LOZANO F., A.M. JUÁREZ, *Instituto de Ciencias Físicas, Universidad Nacional Autónoma de México, P.O Box 43-8, Cuernavaca, Morelos, 62251, México* The field of micro plasmas is currently very active, due to the useful properties and potential applications of micro-hollow cathode discharges. Our group is currently developing these discharge characterization techniques and, as a first obvious starting point, we are performing emission spectroscopy in normal discharges. The focus of this particular contribution is to present a study of vibrational eigenvalues of Morse potential for diatomic molecules. We performed the experimental measurements of these eigenvalues using a high resolution optical monochromator and a parallel plate nitrogen discharge in the glow regime. In particular we determined using this simple arrangement the ro-vibration transitions in N_2, between the electronic states $C^3\Pi_u - B^1\Pi_g$. Moreover, we evaluated theoretically the anharmonic eigenvalues of these transitions using Wigner function for a Morse potential. Based on experimental measurements and making use of the calculated Franck-Condon factors it is possible to extract energy potential parameters of these energy states directly from measured transitions. In particular we have calculated the internuclear separation between the excited states associated with the vibrational transitions observed.

HW1 32 Spectroscopic study of shock waves generated in a supersonic arcjet helium plasma KAZUKI KOZUE, SHINICHI NAMBA, TAKUMA ENDO, KEN TAKIYAMA, *Graduate school of Engineering, Hiroshima University* NAOKI TAMURA, *National Institute for Fusion Science* Recently, we found that the shock cell appeared in an arcjet plasma expanding through a conical-shaped supersonic nozzle. In order to understand the characteristics of the

shock wave, the visible/UV emission spectroscopy was carried out. The arcjet plasma was generated between an anode (copper) and a cathode (Ce/W) with a gap length of 2.5 mm and then expanded through the anode nozzle (throat diameter: 1.0 mm) into low pressure region (expansion section). The discharge current voltage and gas pressure were 40 A $\sim$30 V and $\sim$1000 mbar respectively. A visible spectrometer (focal length: 1.0 m, grating: 2400 grooves/mm) was used to measure the plasma emission The electron temperature was evaluated by Boltzmann plot of He I $2p^3Pnd^3D$ series (n =6, 7, 8 and 9), whereas the density was determined by Stark broadening (He I 438.8 nm). It was found that the density significantly increased at the shock region, which can be expected by the simple gas dynamic theory. However, no distinct change of the temperature was observed.

HW1 33 Optogalvanic spectroscopy: Towards a versatile plasma based tool for gas trace analysis* LINA M. HOYOS-CAMPO, A.M. JUAREZ, *Instituto de Ciencias Fisicas, Universidad Nacional Autonoma de Mexico, P.O Box 43-8, Cuernavaca, Morelos, 62251, Mexico* The real-time detection and quantification of molecular traces in atmospheric samples is currently a very active field in medical, homeland security and biological applications. The optogalvanic effect consists in the variation in the electrical properties of a plasma, induced by the interaction of resonant radiation with atoms or molecules present in it. This technique provides a very sensitive and selective spectroscopic tool for gas trace analysis. However, optogalvanic spectroscopy is not currently being exploited thoroughly, in our opinion, in these applications. In the present contribution we will discuss our current efforts towards developing a molecular trace detection facility focused on gas phase volatile compounds (VOC) detection using optogalvanic spectrometry. Our spectrometer consists of a hollow cathode discharge coupled to tunable lasers in the visible (400-800 nm) and mid-infrared, Quantum Cascade Laser (8000 to 10000 nm) spectral range. In particular we will present our preliminary results in the associative ionization induced in a helium (James Lawler, Phys. Rev. A 22, 3, 1980), as well as an outlook of future work in this emerging area of medical and biological application of gas trace analysis based on optogalvanic spectrometry.

HW1 34 Particle-In-Cell simulation of a magnetized plasma column exhibiting a non-linear rotating structure JEAN-PIERRE BOEUF, BHASKAR CHAUDHURY, *LAPLACE, CNRS and University of Toulouse, France* STANIMIR KOLEV, *University of Sofia, Bulgaria* A two-dimensional Particle-In-Cell Monte Carlo Collisions (PIC-MCC) model is used to study plasma transport across the magnetic field in a magnetized plasma column sustained by energetic electrons emitted from filaments and injected in the central part of the column. The conditions are similar to those of experimental magnetized plasmas studied for example in the MISTRAL device [1]. Experiments show that the boundary conditions at the end of the plasma column (presence of a limiter, applied voltages) play an essential role in the development of instabilities. Because of the 2D nature of the model, the column is supposed to be uniform in the direction parallel to the magnetic field (only flute instabilities can be described), but electron and ion losses at the ends of the plasma column are taken into account self-consistently in the model. Simulations performed under conditions close to those of the experiments of Ref. [1] (argon, pressure 10^{-2} Pa, magnetic field around 20 mT) predict the formation of a rotating electrostatic

plasma structure with spiral arm whose properties are qualitatively and quantitatively close to those observed in the experiments. The model can in particular explain the unexpected distribution of ion velocity measured by Laser Induced Fluorescence in Ref. [1]. We discuss the nature of this instability and its relation with the modified Simon-Hoh instability.

[1]C. Rebont, N. Claire, Th. Pierre, and F. Doveil, Phys. Rev. Lett. **106**, 225006 (2011).

HW1 35 DC breakdown in ethanol vapor* ZORAN PETROVIC, JRELENA SIVOS, NIKOLA SKORO, GORDANA MALOVIC, DRAGANA MARIC, *Institute of Physics University of Belgrade Serbia* DC breakdown is investigated in ethanol vapor at low pressure. Discharge is initiated in parallel-plate electrode system, with copper cathode and transparent conductive anode, 5.4 cm in diameter. The distance between electrodes is adjustable. We present Paschen curve for ethanol measured at electrode separation of 1.1 cm and at pd values between 0.1 Torr cm and 3 Torr cm. Paschen curve has a characteristic shape with a rapid increase of the voltage in the left part and somewhat slower growth in the right-hand branch. The minimum breakdown voltage of 450 V occurs at around pd = 0.35 Torr cm. After breakdown, the discharge operates stable up to pd = 0.7 Torr cm. At higher pd- s, the discharge falls into relaxation oscillations, where it was possible to estimate the breakdown voltages from oscillatory patterns. To investigate elementary processes in the breakdown, for every point of Paschen curve corresponding axial profiles of emission are recorded by ICCD camera. The profiles reveal strong emission peak near the cathode. This indicates that heavy-particle processes play important role in the discharge at all pd values covered by measurements. At the lowest pd values, in the left - hand branch of the Paschen curve, heavy particles (ions, fast atoms and molecules) are dominant.

HW1 36 PLASMA BOUNDARIES: SHEATHS, BOUNDARY LAYERS, OTHERS

HW1 37 Characteristics of wall sheath and secondary electron emission under different electron temperature in Hall thruster PING DUAN, HAIJUAN QIN, ANNING CAO, XINWEI ZHOU, *Department of Physics, Dalian Maritime University* LONG CHEN, *School of Physics and Optoelectronic Technology, Dalian University of Technology* HONG GAO, *Department of Physics, Dalian Maritime University* Characteristics of discharge channel wall plasma sheath in Hall thruster have great effects on its performance. In this paper, we establish a two-dimensional physical model in Hall thruster sheath area to investigate the influences of the different electron temperature, propellant and particle weight on sheath potential and secondary electron emission in Hall thruster, by the method of Particle In Cell (PIC) simulation. And the electric field at the particle position is obtained by solving the Poisson's equation. The numerical results show that when the electron temperature is low, the change of sheath potential drop is bigger than that with electrons at high temperature, the surface potential maintains a stable value and the stability of the sheath is good. When the electron temperature is high, the surface potential maintains persistent oscillation, and the stability of the sheath is reduced. Along with the increase of electron temperature, the coefficient of secondary electron emission in wall reduce after the first

increasing. For three kinds of propellant (Ar, Kr, Xe), with the increase of ion mass, sheath potential and the secondary electron emission coefficient in turn reduce.

HW1 38 Ion velocity distribution function and electric field measurements in a dual-frequency rf sheath* NATHANIEL MOORE, WALTER GEKELMAN, PATRICK PRIBYL, *UCLA Department of Physics* YITING ZHANG, MARK KUSHNER, *Electrical Engineering and Computer Science, U. Michigan* Ion dynamics are investigated in a dual-frequency rf sheath above a 300 mm diameter biased silicon wafer in an industrial inductively coupled (440 kHz, 500 W) plasma etch tool. Ion velocity distribution (IVD) function measurements in the argon plasma are taken using laser induced fluorescence (LIF). Planar sheets of laser light enter the chamber both parallel and perpendicular to the surface of the wafer in order to measure both parallel and perpendicular IVDs at thousands of spatial positions. A fast (30 ns exposure) CCD camera measures the resulting fluorescence with a spatial resolution of 0.4 mm. The bias on the wafer is comprised of a 2 MHz low frequency bias and an adjustable 10-20 MHz high frequency bias. The bias voltages may be switched on and off (f_{rep} up to 1 kHz, duty cycle 10-90%). IVDs are measured with several different bias and timing combinations. For the 2 MHz bias, it was found that the IVD is uniform to within 5% across the wafer. IVDs as a function of phase of the bias were also measured. The electric field in the sheath is measured volumetrically over the wafer at thousands of positions using an emissive probe. The experimental results are compared with a simulation specifically designed for this particular plasma tool.

*Work supported by the NSF and DOE.

HW1 39 On the Ar$^+$ and Xe$^+$ Velocities near the Presheath-Sheath Boundary in an Ar-Xe Discharge JON T. GUDMUNDSSON, *Science Institute, University of Iceland* MICHAEL A. LIEBERMAN, *Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, California 94720, USA* We explore the velocities of positive ions near the presheath-sheath boundary in an Ar-Xe discharge by particle-in-cell/Monte Carlo collision simulation [1]. In the absence of ion-ion collisions, for a pure argon discharge the argon ion has almost the same velocity profile as it does in the mixture of argon and xenon. Similarly, for a xenon discharge the xenon ion has almost the same velocity profile as it does in the mixture of argon and xenon. Thus, each ion reaches its own Bohm speed at the presheath-sheath interface [1] which contradicts the experimental findings of Lee *et al.* [2] where the ion velocities approach the common ion sound speed for both ions in the Ar-Xe discharge. These results have been challenged due to the lack of ion-ion Coulomb collisions in our simulations [3]. We discuss the influence of adding ion-ion Coulomb interactions to the simulation as well as increased electron temperature. We estimate the ion-ion Coulomb collision cross section by a Coulomb momentum transfer cross section and assume isotropic angular distribution of the scattered ions.

[1] J. T. Gudmundsson and M. A. Lieberman, Phys. Rev. Lett. **107**, 045002 (2011).
[2] D. Lee *et al.*, Appl. Phys. Lett. **91**, 041505 (2007).
[3] N. Hershkowitz *et al.*, Phys. Rev. Lett. **108**, 139501 (2012).

HW1 40 Kr ion Laser-Induced Fluorescence using a tunable diode laser near 729 nm for Sheath experiments* GREG SEVERN, CHRIS YIP, *University of San Diego, Dept. of Physics* NOAH HERSHKOWITZ, *University of Wisconsin-Madison, Madison, WI, USA* We have succeeded in obtaining a laser-induced fluorescence (LIF) signal from Kr^+, (83.8 amu) in a low temperature Kr plasma discharge, using a diode laser, for a wavelength near 729 nm. An atomic energy level scheme that is accessible to diode lasers is $^4D_{7/2} \rightarrow {}^4P_{5/2}^0 \rightarrow {}^4P_{5/2}$. The metastable state, $^4D_{7/2}$, proved to be sufficiently populated in a low temperature DC plasma discharge ($T_e \sim 1eV$, $n_i \sim 10^9 cm^{-3}$) to produce a high quality signal. We present results of ion velocity distribution functions (IVDFs) obtained by deconvolution. The principal complication in unfolding an IVDF from the measured LIF signal is the presence of the 4 main isotopic contributions, $^{86}Kr^+$, $^{84}Kr^+$, $^{82}Kr^+$, and $^{80}Kr^+$. Hargus *et al.* [1] have applied deconvolution techniques successfully to Kr II LIF signals from this transition for the case of Hall Thruster plasmas, in which ion temperatures are very large compared with the isotope shifts. Sheath formation experiments (multiple ion species plasmas) will operate in a much cooler regime for which the requirements for deconvolution techniques are more stringent.

*NSF grant nos. PHY-1206421,CBET0903832. and DOE Grant no. DE-SC0001939

[1] W. A. Hargus, Jr. *et al.*, Rev.Sci.Instrum. **83**, 103111 (2012).

HW1 41 Identification of streaming instabilities in the presheath of plasmas with two ion species SCOTT BAALRUD, *Department of Physics and Astronomy, University of Iowa* TREVOR LAFLEUR, *LPP-CNRS, Ecole Polytechnique* A recent theory proposes that ion-ion two-stream instabilities can arise in the presheath of plasmas with two ion species under certain conditions, and that these instabilities rapidly enhance the frictional coupling between the ion species.* The threshold condition for instability onset along with the multi-species Bohm criterion allowed prediction of the speed of each ion species at the sheath edge. These predictions were later confirmed experimentally.† However, recent work has questioned the validity of this theory based on PIC simulations that did not observe instabilities under conditions similar to the experiment.‡ Using numerical solutions for the dispersion relation, we show that this discrepancy is due to a lower electron temperature in the simulations. This identifies an inaccuracy with an approximate instability criterion that predicted instability for the simulation parameters.§ We thoroughly test this numerically. Additionally, for the first time we identify the ion-ion two-stream instabilities in the presheath using PIC simulations.

*Baalrud, Hegna and Callen, Phys. Rev. Lett. **103**, 205002 (2009)
†Yip, Hershkowitz and Severn, Phys. Rev. Lett. **104**, 225003 (2010).
‡Gudmundsson and Lieberman, Phys. Rev. Lett. **107**, 045002 (2011).
§Baalrud, Hegna and Callen, Phys. Rev. Lett.

HW1 42 Magnetized Plasma Sheath Simulation with the Kinetic Finite Mass Method* CHRISTOPHER YOUNG, *Stanford University Plasma Physics Laboratory* DAVID LARSON, *Lawrence Livermore National Laboratory* MARK CAPPELLI, *Stanford University Plasma Physics Laboratory* First results of a magnetized plasma sheath simulation using the Kinetic Finite Mass (KFM) Method are presented. The KFM Method, derived from the Finite Mass Method of [1], is a gridless Lagrangian simulation technique that partitions the system mass into packets that evolve over time. The packets have finite extent in 1D phase space, continuous Gaussian internal mass distributions, and a defining set of Gauss-Hermite quadrature points that move under the action of forces. Much like in a Particle-In-Cell (PIC) approach, the electric field is calculated

by solving Poisson's equation over a temporary grid and the local Lorentz force is mapped back to the particle locations. A Gaussian Mixture Model is employed periodically to reset the Gaussian character of the packets after distortion by the system forces. Sheath results are compared with conventional PIC simulations. This work provides a demonstration of the powerful KFM method in preparation for simulating more complex plasma phenomena.

[1]C. Gauger *et al*. SIAM J. Numer. Anal. **26**, 1744 (2005).

HW1 43 Neutral Resonant Ionization by Excited States in Optically Thick Plasmas

JOHN VOGEL, *University of California (retired)* Ionization from surfaces of low work function explains many properties of both sputter sources of heavy anions and H$^-$ from RF plasma sources for heating magnetically confined plasmas. Surface ionization fails to fully account for intensities and operational peculiarities of either type of ion source, however. A blue plasma above cesium-sputtered material is well associated with intense stable anion beams used in accelerator mass spectrometry (AMS). A theory of neutral resonant ionization within this excited Cs plasma was developed [1] to explain a lack of isotopic fractionation seen in low energy AMS [2]. A similar theory of resonant ionization in hydrogen plasma is possible in which H(2s) atoms, sustained by the optical density of hydrogen for Lyman α radiation, have a path to gas phase production of H$^-$(1s^2) at high rates. The theory depends at present on data from multiple decades of unrelated experiments. Implications of the theory are used to suggest supportive or discrediting experiments.

[1]J. S. Vogel AIP Conf. Proc. 1515: 89 (2013).
[2]J. S. Vogel M *et al*., NIM B294: 340 (2013).

HW1 44 PLASMA DIAGNOSTIC TECHNIQUES

HW1 45 Spectroscopic diagnostics of Ar atmospheric-pressure plasmas using optical emission spectroscopy and collisional-radiative modelin

R. GANGWAR, V. DUMONT, L. STAFFORD, *Universite de Montreal, Montreal (Canada)* UNIVERSITE DE MONTREAL, MONTREAL (CANADA) TEAM Recently, we have studied the physics driving atmospheric-pressure, dielectric barrier discharges applied to the functionalization of wood substrates. In this context, a collisional-radiative (CR) model was developed to describe the evolution of the optical emission spectra and thus to analyze the evolution of the average electron energy in presence of wood outgassing. In this work, a similar approach is used to describe atmospheric-pressure Ar plasmas sustained by either the propagation of a 915 MHz electromagnetic surface wave or controlled by dielectric barrier. In both systems, the measured $2p_x \rightarrow 1s_y$ line intensities in the 500-900 nm range were compared to those predicted by the model accounting for direct excitation, stepwise excitation, energy transfer processes, radiation trapping, and collisional quenching losses. In the microwave plasma, the average electron temperature was found to be slightly larger than that the excitation temperature determined from the Boltzmann plot

using levels 3p, which are generally believe to be in thermal equilibrium with the electrons.

HW1 46 Influence of outgassing on plasma kinetics during wood treatment in dielectric barrier discharges at atmospheric pressure

R. GANGWAR, O. LEVASSEUR, L. STAFFORD, *Universite de Montreal, Montreal (Canada)* N. NAUDE, N. GHERARDI, *LAPLACE - Toulouse (France)* UNIV. DE MONTREAL TEAM, LAPLACE, FRANCE TEAM We have recently extended the range of applications of dielectric barrier discharges (DBD) at atmospheric pressure to the functionalization of wood surfaces with the objective of improving its durability following natural weathering. Having highly complex chemical composition and microstructure, it can release significant amount of impurities, which can play a crucial role on the plasma kinetics, and therefore on the process dynamics. The influence of wood outgassing on the physics driving DBD operated in nominally pure He was investigated using a combination of time-resolved optical emission spectroscopy (OES) and collisional-radiative (CR) modeling. For completely outgassed samples, the He I 588 nm-to-707 nm and 668 nm-to-728 nm line intensity ratios were relatively high early in the discharge cycle, decreased abruptly and then remained stable as the current increased and the discharge eventually extinguished. These results were correlated to a decrease of the electron temperature from about 1 eV early in the cycle to about 0.2 eV in the main discharge lifetime. As wood outgassing evolve, study revealed that the release of products (essentially air) from the wood substrate yields to an increase of the cycle-averaged electron temperature as well as to a significant quenching of He metastable atoms. Selected experiments in presence of trace amounts of N$_2$, O$_2$ and dry-air were also performed to better understand their respective roles.

HW1 47 Mass identification of the neutral products generated in the plasma treatment of polluted atmospheres

DAVID SEYMOUR, *Hiden Analytical* Plasmas produced using Dielectric Barrier Discharge (DBD) devices are very effective in the abatement of air pollution resulting from, for example, the emission of volatile organic compounds (VCOs) by a range of industrial and agricultural processes. The development and monitoring of effective DBD systems can be investigated by advanced mass spectrometric methods specifically configured for analysis at high and atmospheric pressures The present work involves the operation of a small DBD reactor which uses either a helium or nitrogen carrier gas to sustain the plasma to which may be added reactive gases, such as oxygen, as well as samples of pollutants such as chlorinated hydrocarbons, including trichloroethylene. The mass spectrometric analysis was performed using a specially configured system manufactured by Hiden Analytical Ltd. The DBD source may also be combined with a catalyst for plasma-enhanced catalysis. The neutral products of the reactions proceeding in the plasma at atmospheric pressure are sampled through the capillary sampling system which also reduces the pressure of the gas mixture delivered to the ionisation source of the quadrupole mass spectrometer. The ions produced are subsequently mass identified. We describe typical data and comment on the advantages of this technique.

HW1 48 Spatially Resolved Measurements of Emitting Species in Low Temperature Plasma Microjets

SYED HAMID RAZAVI BARZOKI, SOHEILA MOHADES, NAZIR BAREKZI, MOUNIR LAROUSSI, *Old Dominion University* Non-thermal atmospheric pressure plasma microjets have recently been investigated for

plasma processing including biomedical applications [1]. This is due to their ability of providing geometrically well-defined plasma plumes at room temperature and pressure, in air and not confined by electrodes. These microjets can be thought of as vehicles transporting reactive chemical species to a remote substrate. To study the chemical makeup of the plasma Optical Emission Spectroscopy (OES) is used. Since the plasma plume is in fact a series of plasma packets/bullets traveling at high velocities [2], the spatial distribution of the chemical species is a dynamic quantity that varies with the temporal location of the plasma bullet. This is due to substantial changes in size and content that the plasma bullet undergoes as it mixes with the surrounding air along its propagation path. In this paper we present OES measurements of various species generated by a low temperature plasma microjet. The spatial distributions of the emitting species along the axis of propagation of the plasma plume are measured and correlated with the physical position of the plasma bullet.

[1]M. Laroussi and T. Akan, *Plasma Processes and Polymers* **4**, 777 (2007).

[2]X. Lu and M. Laroussi, *J. Appl. Phys.* **100**, 063302 (2006).

HW1 49 Applications of DC-Self Bias in CCP Deposition Systems D.L. KEIL, E. AUGUSTYNIAK, Y. SAKIYAMA, *Lam Research Corporation* In many commercial CCP plasma process systems the DC-self bias is available as a reported process parameter. Since commercial systems typically limit the number of onboard diagnostics, there is great incentive to understand how DC-self bias can be expected to respond to various system perturbations. This work reviews and examines DC self bias changes in response to tool aging, chamber film accumulation and wafer processing. The diagnostic value of the DC self bias response to transient and various steady state current draw schemes are examined. Theoretical models and measured experimental results are compared and contrasted.

HW1 50 Structure of interfacial water molecules under externally-applied electric field studied by vibrational sum—frequency generation TAKAHIRO KONDO, TSUYOHITO ITO, *Osaka University* We report effects of electric field on the structure of water molecules in the CaF_2/water interfacial region by vibrational sum—frequency generation (VSFG) spectroscopy. VSFG gives molecular level information for several layers of molecules at the interface. At the CaF_2/water interface with low pH, the CaF_2 surface is known to be positively charged and form an electric double layer (EDL). Without externally applied electric field, the water molecules are aligned along the electric field inside the EDL (EF-EDL), with facing oxygen (oxygen-up) to CaF_2 surface. According to SFG peak at ~ 3150 cm^{-1} attributed to vibration of highly-ordered water molecules, the orientation of water molecules becomes higher as the external electric field is applied to the same direction of the EF-EDL. In contrast, with the applied field in opposite direction of the EF-EDL, the SFG intensity becomes weak and almost zero. When the applied field is further increased, the SFG intensity becomes stronger with the applied field increasing. This increase suggests that the water molecules can be realigned (oxygen—down to CaF_2 surface) by externally-applied electric field. Details on the experimental results and discussions will be presented at the meeting.

HW1 51 Electric Field Measurement in a Microwave Beam MILKA NIKOLIC, SVETOZAR POPOVIC, LEPOSAVA VUSKOVIC, *Center for Accelerator Science, Department of Physics, Old Dominion University, Norfolk, VA* GREGORY C. HERRING, *NASA Langley Research Center, Hampton, VA* We have developed a simple technique to infer electric field in a polarized microwave beam. The method is based on the measurement of breakdown at the surface of a conducting sphere facing the direction of the field. The concept is based on two approximate relations, the field on the sphere is threefold the ambient field [1], and the breakdown field increases linearly with pressure. The enhancement of the electric field at the sphere is strictly valid for the electrostatic field but is also applicable for the polarized microwave beam when the diameter of the sphere is smaller than the wavelength. It was readily utilized in a number of experiments [2]. The second relation is satisfied when the field frequency is negligible in comparison to the electron collision frequency. We demonstrate the technique by the measurement of axial distribution of the electric field in the beam emitted from a rectangular horn antenna at sub-atmospheric pressure. Measured field distribution is in accordance to the calculation. This technique can be used for free-space beam diagnostics and beam power reduction measurement in the presence of surface plasma at the aperture of the horn.

[1]J. D. Jackson, *Classical electrodynamics, 3rdEd.*, J. Willey and Sons, ISBN 0-471-30932-X.

[2]S. Popović *et al.* Appl. Phys. Lett. **81** (2002) p. 1964.

HW1 52 Electric probe measurements of inductively coupled $Ar/O_2/Ar-O_2$ plasmas: comparison by the interpretation methods of the probe data* TAE HUN CHUNG, MIN WOO SEO, *Dong-A University* Properties of low-pressure inductively coupled argon, oxygen, and Ar-O$_2$ mixture plasmas are investigated using an rf-compensated Langmuir probe measurement. In each gas discharge, the electron energy probability function (EEPF), the plasma density and the electron temperature were obtained by using the probe. The estimates of plasma density determined by using different methods to interpret the probe current-voltage curve are compared. The results show a good agreement between the plasma density values measured in ion saturation current at the floating potential and values measured using other classical methods. Especially, in low-pressure oxygen discharges, the plasma density determined from OML theory compares well with the densities obtained by other methods. At high rf powers, the measured EEPFs for argon, oxygen, and Ar-O$_2$ mixture plasmas were observed to be Maxwellian in the pressure range of 1 - 40 mTorr. The electron temperature was observed to decrease with increasing power and pressure and observed to remain not much changed with increasing Ar content in Ar-O$_2$ plasmas.

HW1 53 Use of "tuned" particle in cell simulations for absolute atomic oxygen number density determination using actinometry* JIM CONWAY, SAMIR KECHKAR, MILES TURNER, STEPHEN DANIELS, *National Centre for Plasma Science and Technology - Dublin City University* Actinometry is an optical diagnostic technique that can be used to quantitatively monitor atomic oxygen number density [O] in plasma. However, careless application of the technique can yield inaccurate information regarding atomic oxygen behavior in the plasma. One limitation on this technique is an accurate knowledge of the rate constants

required, which is in turn hampered by an insufficiently precise knowledge of the plasma Electron Energy Distribution Function (EEDF). In this work Particle in Cell (PIC) simulations are used to generate theoretical EEDFs. To validate a simulation the electron density ne produced by the PIC code is compared to experimental ne values and PIC input parameters adjusted to optimize agreement between the PIC and experimental ne results thus "tuning" the simulation. The resulting EEDF is used to generate rate constants for the actinometry model which should improve the accuracy of the quantitative [O]. This approach was applied to an asymmetric capacitively coupled RF plasma source. The actinometry [O] results are then compared to [O] results obtained using Two-photon Absorption Laser Induced Fluorescence (TALIF) to validate this approach.

HW1 54 Time-Resolved Plasma Density and Magnetic Field Measurements in a Pulsed Plasma Deflagration KEITH LOEBNER, MARK CAPPELLI, *Stanford University* Simultaneous time-resolved measurements of electron density and azimuthal magnetic field strength within a coaxial electromagnetic plasma accelerator operating in a pulsed deflagration mode are presented. Density measurements are performed via an optical interferometer of the Michelson type, while the Faraday rotation of the polarization plane of the same beam is measured in order to provide the magnetic field strength perpendicular to the direction of beam propagation. Experimental data is compared to magnetohydrodynamic simulation results and prior lower fidelity experimental results. Measurements were carried out over a wide range of operating conditions in order to validate the theoretical models describing the physics of the deflagration acceleration mechanism.

HW1 55 Estimation of homogeneous linewidth of the argon $4s[3/2]_2^o - 4p[3/2]_2$ transition by saturation spectroscopy S. NISHIYAMA, *Hokkaid University* M. GOTO, *National Institute for Fusion Science* K. SASAKI, *Hokkaid University* We are developing a Stark spectroscopy system, on the basis of saturation spectroscopy, to measure electric field in argon-containing plasma. Saturation spectroscopy achieves a Doppler-free spectral resolution and a high frequency resolution of the saturation spectrum is required to realize sensitive Stark spectroscopy. In this work, we have investigated the linewidth of the saturation spectrum of the argon $4s[3/2]_2^o - 4p[3/2]_2$ absorption line at various saturation parameters. The plasma source in the experimental apparatus was an inductively-coupled plasma source. The light source was a tunable cw diode laser, and the frequency of the laser was scanned over the Doppler width around the $4s[3/2]_2^o - 4p[3/2]_2$ absorption line (763.51 nm). A small fraction of the laser beam was picked up for a weak probe beam, and the remaining intense beam was used for a pump beam. Homogeneous linewidth without the saturation broadening estimated from the linewidth of the saturation spectrum and the saturation parameter was approximately 10 MHz, while the natural linewidth of this line is 5.5 MHz. Collisional broadening and the instability of the laser frequency are possible reasons of this difference.

HW1 56 Real time monitoring of dielectric-film thickness on the surface of chamber wall for plasma processing JIN-YONG KIM, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* In this study, a dielectric film thickness monitoring system was developed. To measure the thickness of dielectric film on the probe, small sinusoidal voltage signals which have different frequencies are applied to an electrically floated planar type probe, then our system measure current signals and shifted V-I phase. A sheath circuit model is considered in order to measure the dielectric thickness in varying plasma status. In our experiments, accurate dielectric thickness was obtained regardless of RF power, gas pressure and argon-oxygen mixture ratio. This study may helpful to optimize periodic maintenance and increase productivity in semiconductor manufacturing process, such as chemical vapor deposition (CVD) and etching.

HW1 57 A study on measurement of the surface charge accumulation using anodic aluminum oxide template* SEUNG-JU OH, HYO-CHANG LEE, JUN-HYEON MOON, CHIN-WOOK CHUNG*, *Department of Electrical Engineering, Hanyang University, 17 Haengdang-dong, Seongdong-gu, Seoul 133-791, South Korea* SOON-HO KWON, JUNG-JOONG LEE, *Department of Material Science and Engineering, Seoul National University, 131 dong 404 ho, Gwanak-ro 599, Gwanak-gu, Seoul 151-742, South Korea* IL-GYO KOO, SOO-JIN LEE, KYO-SEONG SEONG, *Research center, SEMES, #278 Mosi-ri, Cheonan 331-814, South Korea* PLASMA SURFACE ENGINEERING LAB COLLABORATION, SEMES COLLABORATION As the critical dimension of the nano-device shrinks, an undesired etch profile resulting from the local electric field by the surface charge accumulation is made on the plasma processing. To understand and monitor the surface charge accumulation, the measurement of the voltage difference between top electrode and bottom electrode on the anodic aluminum oxide (AAO) which has high aspect structure is performed in inductively coupled plasma. The voltage difference is changed with external discharge conditions, such as gas pressure, input power, and gas species, and the result is analyzed with the measured plasma parameters.

HW1 58 Cutoff Probe for Tokamak SOL Measurement BYUNG-KEUN NA, KWANG-HO YOU, DAE-WOONG KIM, *KAIST* SHIN-JAE YOU, JUNG-HYUNG KIM, *KRISS* HONG-YOUNG CHANG, *KAIST* Since a cutoff probe was developed, there have been a lot of improvements in methodology and analysis for low temperature plasmas. However, in order to apply the cutoff probe to the Tokamak scrape-off layer (SOL), three important issues should be solved - speed, thermal protection, and short-distance (a few mm) wave propagation in magnetized plasmas. In this presentation, the improvement of cutoff probe for Tokamak is shown. The above problems can be solved using the following methods: (a) the cutoff probe can be used with short impulse of a few nano-seconds for speed improvement. (b) Ceramic covers were used for thermal protection. (c) In magnetized plasmas, the cutoff peak can be analyzed using circuit modeling and CST Microwave studio. To verify the proposed methods, the cutoff probe was applied to a Helicon plasma, and the results were compared to laser Thomson scattering results. Based on the result in the Helicon plasma, the cutoff probe will be applied to far-SOL region at the KSTAR 2013 campaign, and SOL region at the later campaign.

HW1 59 Non-invasive electrical method for measurement of electron temperature in an atmospheric pressure plasma jet source YOUNG-CHEOL KIM, YU-SIN KIM, HYO-CHANG LEE, JUN-HYEON MOON, CHIN-WOOK CHUNG*, *Hanyang*

University Electrical diagnostic method of electron temperature using non-perturbed floating harmonic technique is studied in an atmospheric pressure plasma jet source. When a sinusoidal voltage is applied to the quartz tube which surrounds plasma, the received current has harmonic component. From the relation of the harmonic currents with considerations of the collisional sheath and the applied voltage to the sheath, the electron temperature can be obtained. The measured electron temperature is in the range of 2 - 3 eV in helium discharge.

HW1 60 A new method for measuring pulsed plasma with high-time resolution based on floating harmonic method YU-SIN KIM, CHIN-WOOK CHUNG, *Hanyang University, Republic Korea* A new method in high time resolution of up to 1?sec was proposed in this study to measure plasma density and electron temperature in pulsed plasma. The basic principle of the floating harmonic method is to use the current obtained by applying a sinusoidal voltage to the plasma [1]. The new method is to use boxcar mode method and phase-shifted sinusoidal voltage at regular intervals. When the trigger signal of pulse modulated power source is put in the sinusoidal voltage is applied to plasma. The phase of sinusoidal voltage shifts at regular interval until one cycle of sinusoidal current is obtained at the each time point of micro second. The method can measure plasma parameters in units of 1?sec and the measured results were compared to conventional single Langmuir probe method.

[1]M. H. Lee, S. H. Jang, and C. W. Chung, J. Appl. Phys. 101, 033305 (2007).

HW1 61 Effect of magnetic field on Langmuir probe measurements JEROME BREDIN, PASCALINE GRONDEIN, PASCAL CHABERT, *Laboratoire de Physique des Plasmas* VALERY GODYAK, *RF Plasma Consulting* ANE AANESLAND, *Laboratoire de Physique des Plasmas* In the context of PEGASES thruster where an ion-ion plasma is formed across a localized magnetic field, a study to understand how magnetic field affects the Langmuir probe measurements has been made. Several theoretical works have predict that the plasma anisotropy created by a magnetic field will influence Langmuir probe measurement as a function of the orientation of the probe tip. The study has been made in an electropositive plasma of argon for a uniform magnetic field to avoid effects of magnetic field gradient. The electron energy distribution functions (EEDF) measured with various magnetic field show that the measurements with the probe tip along the magnetic field are depleted in the low energy range compared to the one perpendicular to the magnetic field. Comparison of the results obtained with different magnetic field and different probe orientations allows for evaluation the effect of magnetic field on accuracy of EEDF measurement in plasma with magnetic field. These results confirm the theory on Langmuir probes in magnetized plasma that predict a depletion of low electron energy for measurements along the magnetic field lines.

HW1 62 Characterization of a low pressure Microwave Induced Plasma Discharge AHMED HALA, *KACST* ERDOGAN TEKE, *Sulyman Dimeril University* A low pressure (0.3-7 Torr) Argon gas Microwave Induced Plasma (MIP) discharge was characterized using Optical Emission Spectroscopy (OES). The electron temperature was measured using peak ratio of the Boltzman lines technique. Electron density was measured using the Stark line broadening technique. The electron temperature was found to decrease from 5000 K to around 3000 K for the pressure range of 0.3 to 7 Torr. This is due to the fact that most of the discharge power is directed to ionizing the gas rather than to heating the electrons.

HW1 63 Laser-Induced Fluorescence for Sheath Characterization in Low-Density Argon Plasmas* ALEXANDER C. ENGLESBE, KAPIL U. SAWLANI, JOHN E. FOSTER, *University of Michigan, Ann Arbor* Laser-induced fluorescence (LIF) spectroscopy has become a standard non-intrusive diagnostic technique for determining the energies and concentrations of ion and neutral species in plasmas. A limitation of this technique, however, is the small signal-to-noise ratio incurred when interrogating relatively low-density plasmas. This problem is exacerbated when examining regions such as the sheath at an electrode immersed in the plasma. If ion energetics within the sheath are of interest, then in principle thicker sheaths are desirable in that for a given laser spot size, the potential structure can be inferred with high resolution. We present a methodology for accomplishing LIF in the sheath of a low-temperature argon plasma with an electron density of the order $10^7 - 10^8$ cm^{-3}. This diagnostic is being developed for the purpose of studying the effect of secondary electron emission on sheath potential behavior in low-density plasmas. The plasma in this study is produced in a multipole ring-cusp ion source. A tunable diode laser excites the Ar II transition at 668.61 nm, which fluoresces at 442.72 nm. The LIF measurements of the ion density are corroborated with electrostatic probes at fixed locations, and the ion velocity distribution within the sheath is determined.

HW1 64 Measurement of resonance level densities in rare gas plasmas and modeling of their resulting VUV emissions* J.B. BOFFARD, C.L. CULVER, S. WANG, C.C. LIN, A.E. WENDT, *University of Wisconsin-Madison* S.B. RADOVANOV, H.M. PERSING, *Applied Materials, Silicon Systems Group, Varian Semiconductor Equipment* In the rare gases, the vacuum ultraviolet (VUV) emissions are dominated by the decays from the $1s_2$ and $1s_4$ (Paschen's notation) principal resonance levels. In isolation, atoms excited to these resonance levels have a short radiative lifetime (< 10ns), but resonance blockade of the VUV transitions to the ground state significantly extend the effective lifetimes of these levels under typical plasma conditions with pressures greater than a mTorr. Despite this re-absorption, rare gas plasmas do produce copious VUV emissions that may play an important role in critical surface reactions under certain process conditions. We have measured the resonance level densities as a function of pressure in rare-gas discharges (Ne,Ar,Kr,Xe) in an inductively coupled plasma using both white-light absorption spectroscopy and optical emission spectroscopy by monitoring changes in the $2p_x \rightarrow 1s_y$ branching fractions [1]. The measured resonance level concentrations are subsequently used as inputs to a simple VUV transport model to determine the VUV flux to surfaces. These model VUV flux calculations are compared to measurements made with an absolutely calibrated VUV photodiode.

[1]Plasma Sources Sci. Technol. **18** (2009) 035017.

HW1 65 Stark-effect induced transformation in Rotational Spectra of the Nitrogen Molecule YURI SHCHERBAKOV, LEONID NEKHAMKIN, *None* We present results on spectroscopic studies of filamentary streamer discharge in short air gap

in stage of primary streamer propagation. We have found that the mid-resolved nitrogen second positive system (SPS) spectra emitted from the primary streamer head changes essentially in form within some nanoseconds as compared to typical one. Namely, main peak near the band head formed by the P-branches of Pi3-to-Pi3 transition turns into a widened twin-peak hump; with inessential modification of smooth short-wave part of the SPS-band as whole. Preliminary analysis testifies that such a spectra transformation can be related to Stark-effect under the electric field around 100-300 kV/cm because of splitting of nitrogen rotational terms due to strong mutual perturbation of doubly degenerated Lambda-sublevels affected by the field-induced electric dipole moment. So, this effect might be applicable to determine/estimate electric field and its spatial gradient. Thorough corresponding theory needs to be developed.

HW1 66 Time-resolved measurements of plasma properties in a pulsed argon inductively coupled plasma* A.E. WENDT, C.L. CULVER, S. WANG, J.B. BOFFARD, C.C. LIN, *University of Wisconsin-Madison* Pulsed plasmas present new degrees of freedom (frequency and duty factor) to tailor plasma properties as compared to continuous plasmas. Using optical emission spectroscopy (OES), we have performed time-resolved measurements of the gas temperature, electron temperature, electron density, and number densities of argon $3p^54s$ metastable and resonance level populations [1]. These measurements were made in a 5 mTorr, 500 W average power inductively-coupled argon plasma with a fixed 30% duty factor for modulation periods of 10 μs, 100 μs, 1ms, and 6ms. Effective temporal resolution of the OES-derived values varied from 0.25 μs for the shorter periods to 5 μs for the longer periods. Results are compared with global model estimates [2] and time-resolved Langmuir probe measurements. For the shortest (10 μs) pulse period, the electron, metastable and resonance level densities vary little over the pulse period, but the electron temperature varies by a factor of two. The range of variations in all quantities grow with the length of the pulse period. Results obtained from different sets of emissions lines are used to study transient changes in the EEDF at the start of a pulse.

[1]JVSTA **31** (2013) 021303.
[2]Ashida *et al.*, JVSTA **13** (1995) 2498.

HW1 67 Ion Velocimetry In Magnetized DC Sheaths* CHRISTOPHER YOUNG, ANDREA LUCCA FABRIS, MARK CAPPELLI, *Stanford University Plasma Physics Laboratory* Particle dynamics near the magnetic cusps in cusped field plasma thrusters are still not well understood; characterizing the ion velocity distribution functions in these regions can help thruster designs maximize electron trapping and minimize erosion of the channel wall. To that end, a robust argon ion velocity sensor is developed using a three-level laser-induced fluorescence (LIF) technique. The $3d^4F_{7/2} \rightarrow 4p^4D^0_{5/2}$ ArII transition at 668.61 nm is pumped with a 25 mW tunable external cavity diode laser, and fluorescence down to the $4s^4P_{3/2}$ state at 442.72 nm is collected with phase-sensitive detection. The Doppler shift in the acquired signal peak, compared to a stationary reference, gives the ion velocity component parallel to the exciting laser. We demonstrate this LIF scheme by obtaining the argon ion velocity profile through a magnetized DC sheath. The LIF measurement is used to validate a new optogalvanic velocimetry technique in which two lasers (chopped at different frequencies) intersect one another at 90° in the measurement volume. Using a lock-in amplifier, changes observed in the DC discharge current at

the sum and difference of the two chopping frequencies may be related back to the mean ion velocity at that point.

HW1 68 Measurement of Ion Energy Distribution in Magnetized ICP using Multi-channel Ion Energy Analyzer* WOOHYUN LEE, HYUK KIM, JIWON KIM, HEE WOON CHEONG, *Department of Electrical and Computer Engineering, Seoul National University, South Korea* IL GYO KOO, SOOJIN LEE, HYO-SEONG SEONG, *Research center, SEMES, #278 Mosiri, Cheonan 331-814, South Korea* KI-WOONG WHANG, *Department of Electrical and Computer Engineering, Seoul National University, South Korea* In plasma etch processes, the flux and energy of ions incident on the substrate are the important parameters that control the etch profile and the etch rate. In this regard, retarding field Ion Energy Analyzer (IEA) has been developed and applied to plasma etch. As the size of wafer and etch chamber increase, simultaneous measurement at multi points in radial and poloidal direction becomes important. For this purpose, Plasma lab in Seoul National University and SEMES jointly developed an IEA that can measure the ion energy distributions at five positions in 6-inch wafer at the same time. The IEA is composed of 4 mesh grids (floating, electron repelling, discriminator, secondary electron retarding) and one metal layer (Ion collector). We used a remote controllable voltage source and DAC to supply the stepwise wave form to discriminator voltage source. We used the developed IEA to measure the radial and polodial uniformity of energy distribution of ions incident on the substrate with the change of bias power, gas pressure and bias power frequency.

HW1 69 MOVE ENTIRE ABSTRACT TO HW1.046

HW1 70 Spectroscopic determination of excited atomic states populations in CCP AR discharge KONSTANTIN KURCHIKOV, ALEXANDER KOVALEV, ANNA VASILIEVA, OLEG BRAGINSKY, *Nuclear Physics Institute, Moscow State University, Moscow, Russia* Capacitive Coupled Plasmas (CCP) is being used for plasma processing of different kinds of materials, including low-K films. One of main factors of Low-k damage is ultraviolet radiation of plasma. So control of density of high excited atomic levels is of big importance. For quantitative description of the plasma we have built multilevel Collisional Radiative Model with account of optical thickness effect. The model was tested by comparison of experimentally measured and calculated populations of four first excited levels $3p^54s$ of Ar atom. Levels' populations have been determined experimentally by two methods: 1) measurements of lines intensity for plasmas with different effective sizes, 2) by comparison of intensities with two lines with the same upper level and differently absorbing lower levels. Dependences of levels' populations on plasma parameters have been analyzed.

HW1 71 CAPACITIVELY COUPLED PLASMAS

HW1 72 Resonances and Electromagnetic Field Structure in CCP HF Discharge with Large Electrodes SERGEY DVININ, *Lomonosov Moscow State University* Analytical expressions for

CCP HF discharge impedance, taking into account excitation of surface waves [1], propagating along plasma–sheath–metal interface, and evanescent waves are presented. The waves are experimentally found in ICP plasma in vicinity of large RF electrode in [2]. The well-known plasma-sheath geometrical resonance corresponds to excitation of evanescent waves. Surface waves strongly decay at these conditions. When electrons density increases, skin depth falls. The role of evanescent waves in plasma decreases and the length and energy transferred by surface waves grow. At high plasma density discharge impedance is almost completely defined by surface waves. Influence of even and odd surface take into account. Space charge sheath is described by nonlinear phenomenological model. Specified approach allows to calculate discharge impedance and explains possibilities ambiguity of plasma characteristics, connected with electrodynamic resonances and chemical processes in plasma. It is found, that the role of even and odd waves is defined by geometry of discharge and properties of matching device. Analytical results are compared with numerical modeling.

[1]M.A. Lieberman, J.P. Booth, P. Chabert *et al.*, Plasma Sources Sci. Technol. **11**, 283 (2002).
[2]W. Gekelman, M. Barnes, S. Vincena, and P. Pribyl, Phys. Rev. Lett. **103**, 045003 (2009).

HW1 73 The influence of the secondary electron induced asymmetry on the Electrical Asymmetry Effect in capacitively coupled plasmas JULIAN SCHULZE, *Ruhr-University Bochum* IHOR KOROLOV, ARANKA DERZSI, ZOLTAN DONKO, *Hungarian Academy of Sciences* In geometrically symmetric capacitive radio-frequency plasmas driven by two consecutive harmonics a dc self-bias can be generated as a function of the phase shift between the driving frequencies via the Electrical Asymmetry Effect (EAE). Recently the Secondary Electron Asymmetry Effect (SEAE) was discovered (T. Lafleur, P. Chabert, and J.P. Booth J. Phys. D: Appl. Phys. **46**, 135201 (2013)): unequal secondary electron emission coefficients at both electrodes were found to induce an asymmetry in single frequency capacitive plasmas. Here, we investigate the simultaneous presence of both effects by Particle in Cell simulations, i.e. a dual-frequency plasma driven by two consecutive harmonics with different electrode materials. We find, that the superposition of the EAE and the SEAE is non-linear, i.e. the asymmetries generated by each individual effect do not simply add up. The control ranges of the dc self-bias and the mean ion energy can be enlarged, if both effects are combined.

HW1 74 The effect of structured electrodes on heating and plasma uniformity in capacitive discharges JULIAN SCHULZE, NICO SCHMIDT, EDMUND SCHUENGEL, UWE CZARNET-ZKI, *Ruhr-University Bochum* The effect of structured (non-planar) electrode topologies, e.g. rectangular, rounded, and triangular trenches, on the electron heating dynamics and ion density profile in capacitive radio frequency plasmas is investigated experimentally and by an analytical model. 2D Phase Resolved Optical Emission Spectroscopy is utilized to study the dynamics of energetic electrons inside and outside these structures. In the presence of structured electrodes non-planar RF sheaths form, that affect the electron heating dynamics. We observe a local increase of energetic electrons above the structures caused by a combination of cross-firing of electron beams generated by sheath expansion heating and a temporal confinement of energetic electrons between the sheaths within the structure. The confinement within the trench is limited to the phase of sheath expansion. Also the ionization and, as a consequence the plasma density, are modified by these effects. This is

characterized by radially resolved Langmuir probe measurements and described by a diffusion model. The control of the radial plasma density profile is demonstrated. Via customized electrode topologies high plasma uniformity at specific pressures and heights above the electrode is achieved.

HW1 75 Electron energy balance analysis of ccrf discharge plasmas in oxygen* IGOR SHEYKIN, MARKUS M. BECKER, DETLEF LOFFHAGEN, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* In capacitively coupled radio frequency (ccrf) oxygen plasmas at low pressure the mean electron energy is assumed to be a measure for etching, deposition and other surface processes. Hence, it is important to know its spatio-temporal distribution, dependence on applied voltage and discharge parameters. Here, an axially and phase resolved analysis of the mean electron energy has been performed by means of fluid modelling for discharge plasmas in a reactor with plane parallel electrodes. The model includes the coupled system of balance equations for heavy species, the electron component and the mean electron energy as well as Poisson's equation with the corresponding boundary conditions. The analysis has been done for pressures between 30 and 50 Pa, applied voltage amplitudes from 100 to 500 V and a frequency of 13.56 MHz. The impact of the different contributions to the electron energy balance is discussed. In particular, it was found that the ratio between energy gain due to Joule heating and energy flux in the plasma bulk depends strongly on the applied voltage and pressure of the gas.

HW1 76 Electron and ion dynamics in a multi-frequency low-pressure asymmetric capacitively coupled oxygen plasma ANDREW GIBSON, *Centre for Plasma Physics, Queen's University Belfast* ARTHUR GREB, *York Plasma Institute, University of York* WILLIAM GRAHAM, *Centre for Plasma Physics, Queen's University Belfast* TIMO GANS, *York Plasma Institute, University of York* Multi-frequency plasma sources are widely used in industrial processes. Most current implementations apply two significantly differing frequencies to avoid coupling between the frequency components and achieve separate control of electron and ion dynamics. However, at very high driving frequencies plasma non-uniformities may be produced as a result of electromagnetic effects involving the high-frequency component. Thus further investigation and understanding of the coupling between multiple lower frequencies, where electromagnetic effects are minimised is warranted. Presented here is a study of a capacitively coupled oxygen plasma using a voltage waveform comprised of multiple frequencies below the threshold required to induce significant electromagnetic effects in current generation plasma processing reactors. Plasma dynamics are simulated using a hybrid model of an asymmetric CCP. Simulations are performed in time over a 1D spatial domain across the discharge centre. The asymmetry in the model is comparable to our experimental setup (GEC reference cell). The effect of variations in the relative amplitude of each frequency component and also in the phase difference between the components on electron and ion dynamics within the excitation cycle is investigated and discussed.

HW1 77 Simulation model for analyzing voltage-current characteristics of the barrier type lamp filled with Hg-Ar gas YOSHIO WATANABE,* *Kanagawa University Professor* TOMOHIRO YAMAGUCHI,† RYOSUKE IMADA,‡ *Kanagawa University* The simulation model for DBD lamp filled with Hg-Ar gas is studied. The straight tube filled with Hg and Ar gases is employed

as a lamp. Three kinds of applied voltage waveforms at high frequency are applied between the pair of stripe electrodes attached on the outside of the tube. One dimensional model is employed. Ionization frequency based on Townsend ionization coefficient is employed in this model. A try-and-error method is employed to estimate the value of each coefficient, and the calculated waveform is compared with the measured current waveform. The values by which the most similar current waveform to the measurement is obtained are selected as appropriate values. Using these coefficient values, the discharge current waveforms by the applying voltage with triangular waveform and trapezoidal waveforms are calculated and compared with the measured current waveforms. Good agreements between the calculation and the measurement in discharge current waveform are obtained for three types of applied voltage waveform. Then, the distributions of electric field, electron density and ion density in the discharge space are calculated. It is shown that the space charge layer is formed on the glass tube wall and ionization takes place mainly in the space charge layer.

* Professor
† Assistant Professor
‡ Graduated Student

HW1 78 The effect of dust on the electron heating in capacitively coupled H_2/SiH_4 single- and dual-frequency discharges* EDMUND SCHÜNGEL, SEBASTIAN MOHR, SHINYA IWASHITA, JULIAN SCHULZE, UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr-University Bochum* Hydrogen diluted silane discharges exhibit a high dust concentration under typical application conditions. Therefore, the role of dust in fundamental plasma processes needs to be understood. We study a capacitively coupled rf discharge in H_2/SiH_4 using Phase Resolved Emission Spectroscopy, two-dimensional laser light scattering on the dust particles as well as current and voltage measurements. The results show that the electron heating is strongly affected by the presence of dust particles. In particular, a mode transition occurs from the traditional α-mode to a bulk drift field mode (Ω-mode), if the amount of dust is increased. An analytical model of the electron dynamics in Ω-mode has been developed. An asymmetric dust particle density profile, e.g. due to a gas temperature gradient, induces an asymmetry in the electron heating and, thereby, in the ion density profile of a single frequency parallel plate discharge. In electrically asymmetric discharges, the discharge asymmetry can usually be controlled via the phase angle between the applied harmonics. It is found that the Electrical Asymmetry Effect works in discharges operated in both α- or Ω-mode, as the width of the control interval is almost independent of the dust distribution.

HW1 79 Multi-Peaked Distributions of Escaping Electrons in RF-DC Discharge ALEXANDER V. KHRABROV, IGOR D. KAGANOVICH, *Princeton Plasma Physics Laboratory* PETER L.G. VENTZEK, LEE CHEN, *Tokyo Electron America* Hybrid RF-DC capacitively coupled discharges find important and growing technological applications. In RF-DC systems, secondary electrons emitted from electrodes undergo complicated motion defined by acceleration in, and bouncing between a steady and an oscillating sheath. For the emitted electrons that return to, and impinge upon the RF electrode, the arrival energy is a non-monotonic function of the driving phase at which they were emitted. This basic property

leads to a velocity distribution with multiple peaks [1,2]. Such effect may explain the peaks in electron energy distributions measured in RF-DC system at the RF electrode [2,3]. In particular, the distribution of secondary electrons is sensitive to variations in the bouncing time, and may form several peaks if even a small high-frequency ripple is present in the RF sheath voltage [2], as may be the case due to the plasma-sheath resonance (PSR). We have found such features in test-particle simulations of the discharge, and analyzed the observed distributions.

[1]D. Israel *et al.*, J. Appl. Phys. **99**, 093303 (2006).
[2]K. E. Orlov and A. S. Smirnov, Plasma Sources Sci. Technol. **10**, 541 (2001).
[3]L. Xu *et al.*, Appl. Phys. Lett. **93**, 261502 (2008).

HW1 80 OTHER PLASMA SCIENCE TOPICS

HW1 81 Reflection of Slow Electrons from Solid Surface* ALEXANDER MUSTAFAEV, MATSAK AINOV, *St.-Petersburg State Mining University* IGOR KAGANOVICH,† *Plasma Physics Laboratory Princeton University* VLADIMIR DEMIDOV, *WVU USA* Given that progress of future plasma technologies depends on control of electron coefficient reflection r_0, the development of methods of measurement and control of r_0 is of great importance. Published experimental data on r_0 for slow electrons are inconsistent and sometime give large values up to $r_0 \approx 0,8$ and even higher. This talk presents a technique for r_0 measurements in low pressure plasmas in the presence of transverse magnetic field. It is found that for poly-crystal surface, effective reflection coefficient can really reach value of 0.8. It is demonstrated that it is connected to additional reflection from potential barrier near the surfaces. The contribution of electron reflection from the barrier and the surface has been divided and studied. The data have been confirmed at different mono-crystal surfaces.

HW1 82 A method for gas analysis in nonlocal plasma of a short argon microdischarge* ANATOLY KUDRYAVTSEV, *St. Petersburg State University* MARGARITA STEFANOVA, PETKO PRAMATAROV, *Institute of Solid State Physics, Sofia, Bulgaria* Recently developed collisional electron spectroscopy (CES) method allows identification of gas impurities in a main gas in nonlocal plasma, where the different groups of electrons do not relax in energy by collisions in the volume and behave independently of each other. The fast electrons, released in processes of Penning ionization of the impurity particles by main gas metastable atoms, give narrow peaks in the EEDF near the energy of their appearance. Selective registration of groups of fast nonlocal electrons created in Penning ionization of the impurity atoms or molecules by metastable argon atoms is carried out. Argon is used as a main gas. The negative glow plasma of a short dc microdischarge at medium pressures is used as most suitable medium for nonlocal formation of the EEDF. Penning reactions with known gas impurities and sputtered cathode metal atoms are registered. The obtained maxima in the EEDF appear at the characteristic energies corresponding to the expected maxima for penning electrons of the known gas impurities used. This experiment contributes to the development of new microdischarge

gas analyzer for gas impurities detection, whose dimensions can be dramatically reduced, compared to the exciting devices.

*AAK thanks FZP and SPbSU for support.

HW1 83 PLASMAS FOR NANOTECHNOLOGIES, FLEXIBLE ELECTRONICS AND OTHER EMERGING APPLICATIONS

HW1 84 Microwave plasma produced carbon nanostructures JULIO HENRIQUES, ELENA TATAROVA, *Institute of Plasmas and Nuclear Fusion, Instituto Superior Tecnico, Technical University of Lisbon, Portugal* CLAUDIA LUHRS, JONATHAN PHILLIPS, *Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA 93943, USA* ANA REGO, ANA FERRARIA, *Centro de Quimica-Fisica Molecular and IN, Instituto Superior Tecnico, Technical University of Lisbon, Portugal* MIROSLAV ABRASHEV, *Faculty of Physics, Sofia University, Sofia, Bulgaria* ANA DIAS, CARLOS FERREIRA, *Institute of Plasmas and Nuclear Fusion, Instituto Superior Tecnico, Technical University of Lisbon, Portugal* A microwave, atmospheric argon plasma driven by surface waves has been used for synthesizing carbon nanostructures by passing vaporized ethanol through the plasma. The method is based on sending vaporized ethanol molecules through a microwave argon plasma environment, where decomposition of ethanol molecules takes place and carbon atoms are created. These carbon atoms agglomerate subsequently in the outlet gas stream to form nanostructures that are collected by nylon membrane filters. External, forced cooling/heating has been applied using a cryostatic system to fix the temperature in the nucleation zone of the plasma reactor. The synthesized carbon nanostructures were analyzed by high-resolution transmission electron microscopy (HRTEM), X-ray photoelectron spectroscopy (XPS), and micro-Raman spectroscopy. Graphene sheets and carbon nanoparticles have been selectively synthesized through the control of the outlet plasma stream temperature.

HW1 85 Microwave plasma based method for free standing graphene synthesis ELENA TATAROVA, JULIO HENRIQUES, *Institute of Plasmas and Nuclear Fusion, Instituto Superior Tecnico, Technical University of Lisbon, Portugal* CLAUDIA LUHRS, JONATHAN PHILLIPS, *Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA 93943, USA* ANA REGO, ANA FERRARIA, *Centro de Quimica-Fisica Molecular and IN, Instituto Superior Tecnico, Technical University of Lisbon, Portugal* MIROSLAV ABRASHEV, *Faculty of Physics, Sofia University, Sofia, Bulgaria* ANA DIAS, CARLOS FERREIRA, *Institute of Plasmas and Nuclear Fusion, Instituto Superior Tecnico, Technical University of Lisbon, Portugal* Microwave atmospheric pressure plasmas driven by surface waves were used to synthesize graphene sheets from vaporized ethanol molecules carried through argon plasma. In the plasma ethanol decomposes creating carbon atoms that form nanostructures in the outlet gas stream. The synthesized carbon nanostructures were analysed using high-resolution transmission electron microscopy (HRTEM), X-ray photoelectron spectroscopy (XPS), and micro-Raman spectroscopy. The existence of few layer graphene (from one to five sheets) has been confirmed by HRTEM images. Raman spectral studies were conducted to determine the ratio of the 2D to G peaks. Furthermore, the C 1s XPS region is dominated by the peak centred

at 284.4 eV assigned to sp^2 carbon atoms bond to carbon. Forced external heating of the outlet gas stream results in an increase of the sp^2/sp^3 (> 4) and C/O (> 14) ratios. Analysis of the C 1s XPS energy loss spectra reveals plasmon energy losses attributed to π-π^* collective excitation.

HW1 86 Plasma-water interactions at atmospheric pressure in a dc microplasma JENISH PATEL, *University of Ulster, UK* LUCIE NĚMCOVÁ, *Brno University of Technology, Czech Republic* SOMAK MITRA, *University of Ulster, UK* WILLIAM GRAHAM, *Queen's University Belfast, UK* PAUL MAGUIRE, *University of Ulster, UK* VLADIMIR ŠVRČEK, *The National Institute of Advanced Industrial Science and Technology (AIST), Japan* DAVIDE MARIOTTI, *University of Ulster, UK* Plasma-liquid interactions generate a variety of chemical species that are very useful for the treatment of many materials and that makes plasma-induced liquid chemistry (PiLC) very attractive for industrial applications. The understanding of plasma-induced chemistry with water can open up a vast range of plasma-activated chemistry in liquid with enormous potential for the synthesis of chemical compounds, nanomaterials synthesis and functionalization. However, this basic understanding of the chemistry occurring at the plasma-liquid interface is still poor. In the present study, different properties of water are analysed when processed by plasma at atmospheric-pressure with different conditions. In particular, pH, temperature and conductivity of water are measured against current and time of plasma processing. We also observed the formation of molecular oxygen (O_2) and hydrogen peroxide (H_2O_2) for the same plasma conditions. The current of plasma processing was found to affect the water properties and the production of hydrogen peroxide in water. The relation between the number of electrons injected from plasma in water and the number of H_2O_2 molecules was established and based on these results a scenario of reactions channels activated by plasma-water interface is concluded.

HW1 87 Microplasma surface engineering of silicon nanocrystals for improved inorganic/polymer nanocomposites SOMAK MITRA, *University of Ulster* VLADIMIR SVRCEK, *National Institute of Advanced Industrial Science and Technology (AIST)* PAUL MAGUIRE, DAVIDE MARIOTTI, *University of Ulster* VLADIMIR SVRCEK COLLABORATION Improved optoelectronic properties have been achieved by direct current (DC) microplasma-induced 3-dimesional (3D) surface engineering of silicon nanocrystals (SiNCs) in water with (Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate)) (PEDOT:PSS). Specifically, we have successfully shown that photoluminescence (PL) of SiNCs inside a water-based solution increases after microplasma processing. The experimental results show that optical properties of SiNCs do not deteriorate over time and remain stable in water with potential application impact for bio-related applications. We have also shown that fast oxidation process in water is prevented over longer period of time due to the microplasma processing in comparison to the unprocessed sample. Furthermore, the improved surface characteristics allow for the formation of water-soluble nanocomposites with improved opto-electronic properties; this can have direct implications for higher performance opto-electronic devices including solar cells.

HW1 88 Development and characterization of a neutral beam source for sub-10 nm etching* DANIIL MARINOV, ZIAD EL OTELL, NICHOLAS ST. BRAITHWAITE, MARK BOWDEN, *Department of Physical Sciences, The Open University, Walton*

Hall, Milton Keynes, MK7 6AA, UK Neutral beam etching is a promising technology for damage-free sub-10 nm device fabrication. In this work a neutral beam is generated by surface neutralization of ions extracted from a pulsed ICP discharge in Ar/SF_6. Negative ions are extracted during the afterglow phase when an ion-ion plasma is formed. The evolution of the density of various charged species is measured with different techniques (Langmuir, hairpin and ion flux probes). High density plasma, with electron number density in the range 10^{17} - 10^{18} m^{-3}, is typically produced in the pulsed ICP. The electron heating in the active-glow phase is characterized using trace rare gas optical emission spectroscopy with Ar, Kr and Xe admixtures. The energy spectra and fluxes of the extracted ions are measured using a retarding field analyzer. The potential of pulse tailoring of the discharge for optimization of negative ion formation is investigated, while varying the extraction pulse waveform provides another degree of freedom to obtain desirable neutral beam characteristics. Finally, the etching performance of the neutral beam source is demonstrated on patterned and non-patterned silicon wafers.

HW1 89 SPECIAL ARRANGED SESSIONS

HW1 90 Odd Length Contraction FLORENTIN SMARANDACHE, *University of New Mexico* Let's denote by V_E the speed of the Earth and by V_R the speed of the rocket. Both travel in the same direction on parallel trajectories. We consider the Earth as a moving (at a constant speed $V_E - V_R$) spacecraft of almost spherical form, whose radius is r and thus the diameter $2r$, and the rocket as standing still. The non-proper length of Earth's diameter, as measured by the astronaut is: $L = 2r\sqrt{1 - \dfrac{|V_E - V_R|^2}{c^2}} < 2r$. Therefore Earth's diameter shrinks in the direction of motion, thus Earth becomes an ellipsoid - which is untrue. Planet Earth may increase or decrease its diameter (volume), but this would be for other natural reasons, not because of a... flying rocket! Also, let's assume that the astronaut is laying down in the direction of motion. Therefore, he would also shrink, or he would die!

HW1 91 Ion distribution functions in magnetized rf Argon plasma presheaths* M. UMAIR SIDDIQUI, NOAH HERSHKOWITZ, *University of Wisconsin - Madison* A helicon plasma source was operated in a low power inductive mode to create a magnetized Argon plasma with densities of $10^{11} - 10^{12}$ cm^{-3} and electron temperatures from $3 - 5$ eV. A grounded plate oriented perpendicular to the axial magnetic field was placed 2.5 antenna lengths downstream from the near edge of the rf antenna. Using laser-induced fluorescence, the ion velocity distribution functions were investigated along the axis of the chamber in the bulk plasma and in the plate's presheath. Bimodal and non-Maxwellian distribution functions were observed in the presheath, though not in the bulk plasma. In certain situations ion populations traveling in opposite directions were observed. In this work the authors investigate these phenomena as a function of neutral pressure, rf power and axial magnetic field strength.

SESSION IW1: PPPL DIRECTOR WELCOME AND GEC FOUNDATION TALK
Wednesday Morning, 2 October 2013; Room: Ballroom I & II at 10:00; Igor Kaganovich, Princeton Plasma Physics Laboratory, presiding

Invited Papers

10:00
IW1 1 The path to magnetic fusion energy
STEWART PRAGER, *Princeton Plasma Physics Laboratory, Princeton University*

Progress in magnetic fusion energy has progressed sufficiently far that we can identify an R&D roadmap that will take us the rest of the way toward commercial power production. Our progress is illustrated clearly by our capability to design and construct ITER - a tokamak experiment that will produce burning plasmas (where the plasma temperature is mainly self-sustained by heating by fusion-produced alpha particles) and generate 500 MW of fusion power for about 500 seconds. This reactor-scale experiment will be the centerpiece of the world fusion program, beginning plasma operations in the early 2020s. Remaining challenges include (1) producing high performance plasmas in steady state (with research aided by the new class of tokamak and stellarator experiments with superconducting magnets in Asia and Europe), (2) establishing a suitable plasma-material interface, with suitable materials and plasma control (successfully demonstrated for existing short-pulse experiments, but not yet for steady state), (3) developing the material science and integrated engineering systems to withstand and manage the large flux of neutrons. Planning in several nations outline R&D programs that lead to demonstration power plants around the late 2030s. This talk will review the recent progress, remaining scientific challenges, and the remaining path to take us to a demonstration power plant.

10:30
IW1 2 Thinking and doing, a long way to the top in commercialisation
ROD BOSWELL, *Australian National University*

A university's primary role is to educate and produce research results, mostly funded by the common weal. A business's primary role is to survive. Generally business wants ideas that help with their immediate problems into a 3 month

foreseeable future. Universities are used to timescales at least an order of magnitude longer. The speaker's experience as lead guitar in a rock and roll band, building cars, running an offset printing firm, the helicon source and interacting with a Large American Manufacturer will be presented. His university research and development of a plasma source focussed ion beam, the creation of a start-up "Oregon Physics," the subsequent industrial development and commercialisation, the distasteful legal wrangles about IP and the eventual emergence of OP into the sunshine of a successful operation will be described.

SESSION JW1: GEC BUSINESS MEETING
Wednesday Morning, 2 October 2013
Room: Ballroom I & II at 11:30
Amy Wendt, University of Wisconsin-Madison, presiding

Contributed Papers

11:30
JW1 1 GEC Business Meeting

SESSION KW1: INDUCTIVELY COUPLED PLASMAS
Wednesday Afternoon, 2 October 2013
Room: Ballroom I at 13:30
Steven Shannon, North Carolina State University, presiding

Contributed Papers

13:30
KW1 1 ICP Source with Immersed Ferromagnetic Inductor
VALERY GODYAK, *RF Plasma Consulting* Inductively coupled plasma (ICP) sources have found a wide range of applications in various areas of plasma science and technology. Among different ICP topology, ICPs with immersed inductors have benefits (compared to ICPs with helical side or flat top inductors) of better coupling and electromagnetic (EM) field self-screening by the plasma surrounding the inductor. This allows for EM-free otter plasma boundary, thus making an ICP chamber entirely of metal or glass, with no EM radiation outside the plasma. It's been long known that ICP enhanced with ferromagnetic core immersed inductor is applicable in rf light sources and has demonstrated good performance. In this presentation we report a detailed experimental study of the electrical and plasma characteristics of compact ICPs with immersed ferromagnetic inductors in argon and xenon gas. The extremely high plasma transfer efficiency of this plasma source has been demonstrated in a wide range of gas pressure and rf power. A compact plasma cathode built with ICP having an immersed ferromagnetic inductor, and operating at 70-200 W has shown high power transfer efficiency of 97%, and electron emission efficiency of 25 mA/W. These data are superior compared to those demonstrated for other plasma cathodes.

13:45
KW1 2 Three-coil inductively coupled plasma (ICP) source with individually controlled coil currents supplied from a single power generator LEONID DORF, SHAHID RAUF, JONATHAN LIU, JASON KENNEY, STEVEN LANE, ANDREW NGUYEN, KARTIK RAMASWAMY, KEN COLLINS, *Applied Materials* As requirements on plasma uniformity get more stringent in the semiconductor industry, an ICP source with 3 coils becomes warranted. Designing a power distribution/50Ω-tuning network (PDN) that delivers the power from a single generator to 3 coils is complicated, due to inductive coupling between the coils, and between coils and

plasma. Our PDN comprises several capacitors, including 2 variable ones, $C_{1,2}$, connected in parallel to 2 coils. A set of equations for coils/plasma currents was solved over a wide parameter space to determine practical values/ranges for all capacitors. It was shown that by moving along a pre-determined programming path in $C_{1,2}$ space, one can attain various coil current ratios (CCR) without crossing resonance curves. The latter causes coil current reversal, which may result in plasma instabilities and affect uniformity. Based on modeling results, the PDN was built and tested using a specially made 3-coil source. A wide range of CCR was achieved by varying $C_{1,2}$, including maxima or minima in any 2 coils. With slight adjustments (to account for parasitics and actual plasma coupling), the model correctly predicted experimentally observed CCR for each tested $C_{1,2}$ pair. Likewise, the theoretical resonance structure was reproduced experimentally with good agreement.

14:00
KW1 3 Synergistic Behavior of a Dual Tandem Plasma Source* LEI LIU, WEIYE ZHU, SHYAM SRIDHAR, VINCENT DONNELLY, DEMETRE ECONOMOU, *University of Houston* MICHAEL LOGUE, MARK KUSHNER, *University of Michigan* The electron energy distribution function (EEDF) is of paramount importance in plasma processing. To control the EEDF, a dual plasma source was developed, consisting of a lower (main) inductively coupled plasma (ICP), in tandem with an upper ICP. The two sources were separated by a grounded metal grid. A boundary electrode (BE) in the upper source could be DC biased to inject charged species between the two sources, in an effort to control the EEDF of the lower (main) source. A Langmuir probe was employed to measure plasma parameters and the EEDF in Ar plasmas. It was found that, without any bias on the BE, low energy electrons were depleted in the main source when both plasmas were cw powered. The low energy electron population in the main source increased with increasing positive BE bias. The reverse behavior was observed in the upper source. The main source was also power modulated at 10 kHz with 20% duty cycle, while the upper plasma was cw powered. Low (0.2-0.8 eV), almost constant T_e was obtained in the afterglow of the main source, with high plasma density ($\sim 10^{11}$ cm^{-3}) at 10 mTorr. T_e could be controlled by varying the BE bias. Simulations using the Hybrid Plasma Equipment Model agreed with experimental data and provided valuable insights regarding the interaction between the two sources.

*Work supported by DOE Plasma Science Center and NSF.

14:15
KW1 4 Large and powerful RF-driven hydrogen ion sources URSEL FANTZ, PETER FRANZEN, BERND HEINEMANN, *Max-Planck-Instiut fuer Plasmaphysik, EURATOM Association, Boltzmannstr. 2, 85748 Garching, Germany* NNBI TEAM Large area plasma sources are desirable in many applications among them the heating systems of magnetically confined fusion devices such as ITER (www.iter.org). Here, the hydrogen plasma has to illuminate homogeneously an area of 1.9×1 m^2 at a pressure of 0.3 Pa maximum. The plasma is generated via inductively coupling in

WEDNESDAY AFTERNOON \ KW1

eight cylindrical drivers, each driver powered with up to 90 kW power at 1 MHz frequency. The modular concept allows for size scaling such that large surfaces are homogeneously illuminated. The ELISE test facility, recently commissioned at IPP, is equipped with a source of the same width but half the height of the ITER source, i.e. an area of 1×1 m². Target parameters in hydrogen and deuterium plasmas are high dissociation degree and high ionization degree: atomic to molecular density ratio of about 0.2 and a ratio of electron to neutral density of about $0.01 - 0.1$, respectively. The electron temperature and density are intended to decrease from about 10 eV and 10^{18} m⁻³ in the drivers to 1 eV and 10^{17} m⁻³ close the extraction surface by using a magnetic filter field. The plasma uniformity and the plasma parameters are measured by optical emission spectroscopy using multiple lines of sight allowing also for tomographic studies. The influence of surface bias and the influence of a magnetic filter field on the plasma uniformity is investigated as well.

14:30
KW1 5 Measurements of collisionless heating effects in the H-mode of an inductively coupled plasma system MUJAHID ZAKA-UL-ISLAM, *Physics Department, Faculty of Science, Jazan*

University, Jazan, 2079, Saudi Arabia BILL GRAHAM, *Centre for Plasma Physics, Queen's University Belfast, Northern Ireland, UK* TIMO GANS, KARI NIEMI, DEBORAH O'CONNELL, *York Plasma Institute, University of York, Heslington York, UK* Inductively coupled plasma systems (ICPs) for processing applications are often operated at low pressures, in the near-collisionless regime. In this regime, the electron mean free path is comparable or larger than the plasma dimensions. The electron dynamics in such ICPs has been investigated here, using phase and space resolved optical emission spectroscopy (PROES) and Langmuir probe measurements. The PROES measurements are also used to calculate the Fourier harmonics components of the 2D excitation (in the radial axial plane). The experimental system is a standard GEC cell with the axial gap of ∼4 cm, powered by 13.56 MHz RF power supply. The gas pressure was varied between $0.5 - 2$ Pa. The PROES measurements and Fourier harmonics components confirm many of the previous simulation results in comparable operational regimes. The results show that in the 2D (radial-axial) plane, the plasma power is deposited in a spatially non-uniform and non-linear manner, with axial layers of positive and negative power absorption. The contribution of these nonlinear effects decreases with an increase in the pressure, as observed in previous experimental and simulation results.

SESSION KW2: MICRODISCHARGES II
Wednesday Afternoon, 2 October 2013; Room: Ballroom II at 13:30; Teresa Delosarcos, Ruhr University, presiding

Invited Papers

13:30
KW2 1 Interactions Between Small Arrays of Atmospheric Pressure Micro-Plasma Jets: Gas Dynamic, Radiation and Electrostatic Interactions*
NATALIA BABAEVA, *University of Michigan*

Atmospheric pressure plasma jets are widely used devices for biomedical applications. A typical plasma jet consists of a tube through which noble gas or its mixture with a molecular gas flows. The noble gas creates a channel into the ambient air which is eventually dispersed by interdiffusion with the air. Plasma plumes are formed by the propagation of ionization waves (IWs) through the tubes and then through the noble gas phase channel. The IW typically propagates until the mole fraction of the ambient air in the channel increases above a critical values which requires a larger E/N to propagate the IW. By grouping several jets together to form an array of jets, one can in principle increase the area treated by the plume. If the jets are sufficiently far apart, the IWs and resulting plasma plumes are independent. As the spacing between the jets decreases, the plasma jets begin to mutually interact. In this talk, we discuss results from a computational investigation of small arrays of He/O_2 micro-plasma jets propagating into ambient air. The model used in this work, *nonPDPSIM*, is a plasma hydrodynamics model in which continuity, momentum and energy equations are solved for charged and neutral species with solution of Poisson's equation for the electric potential. Navier-Stokes equations are solved for the gas dynamics and radiation transport is addressed using a propagator method. We found that as the spacing between the jets decreases, the He channels from the individual jets tend to merge. The IWs from each channel also merge into regions having the highest He mole fraction and so lowest E/N to sustain the IW. The proximity of the IWs enable other forms of interaction. If the IWs are of the same polarity, electrostatic forces can warp the paths of the IWs. If in sufficient proximity, the photoionization from one IW can influence its neighbors. The synchronization of the voltage pulses of adjacent IWs can also influence its neighbors. With synchronized pulses, adjacent IWs can simultaneously travel along their common single stream or their separate helium channels. If the voltages pulses are not synchronized, adjacent IWs may be extinguished or enhanced, depending on the timing and polarity of its neighbors.

Contributed Papers

14:00
KW2 2 Modeling the excitation dynamics of micro structured atmospheric pressure plasma arrays* ALEXANDER WOLLNY, RALF PETER BRINKMANN, *Institute for Theoret-*

ical Electrical Engineering Micro structured atmospheric pressure plasma arrays have been developed by J.G. Eden and co-workers as efficient light sources [1]. In essence, this device forms an array of dielectric barrier discharges: a silicon wafer with a matrix of cavities is covered by dielectrics. The counter electrode grid is embedded in the dielectrics. It is driven by alternating voltage

at a frequency of 10-100 kHz in argon at atmospheric pressure. To the naked eye these devices appear to glow homogeneously. However, phase resolved optical emission spectroscopy performed by V. Schulz-von der Gathen and co-workers [2] revealed strong dynamics. The model presented here addresses each cavity independently: cavities are described by a one dimensional drift model. Interactions, mainly driven by photon transport, are treated in a separate model that couples back to the individual cavity models. This allows us to investigate the individual discharge as well as the experimentally observed ionization wave propagation. Both will be addressed in this work.

[1]J. G. Eden *et al., J. Phys. D: Appl. Phys.* **38** 1644 (2005).
[2]H. Boettner *et al., J. Phys. D: Appl. Phys.* **43** 124010 (2010).

14:15
KW2 3 Bulk heating of electrons in capacitive radio frequency atmospheric pressure microplasmas TORBEN HEMKE, DENIS EREMIN, THOMAS MUSSENBROCK, *Ruhr-University Bochum* ARANKA DERZSI, ZOLTAN DONKO, *Hungarian Academy of Sciences* KRISTIAN DITTMANN, JUERGEN MEICHSNER, *University of Greifswald* JULIAN SCHULZE, *Ruhr-University Bochum* Electron heating and ionization dynamics in capacitively coupled radio frequency atmospheric pressure microplasmas operated in helium are investigated by particle-in-cell simulations and semi-analytical modeling. A strong heating of electrons and ionization in the plasma bulk due to high bulk electric fields are observed at distinct times within the RF period. Based on the model the electric field is identified to be a drift field caused by a low electrical conductivity due to the high electron-neutral collision frequency at atmospheric pressure. Thus, the ionization is mainly caused by ohmic heating in this "Ω-mode." The phase of strongest bulk electric field and ionization is affected by the driving voltage amplitude, which determines the resistivity of the discharge via its effect on the plasma density. At high voltage amplitudes the ionization peaks at the sheath edges due to a decrease of the ion density towards the electrodes. Significant analogies to electronegative low-pressure macroscopic discharges operated in the drift-ambipolar mode are found, where similar mechanisms induced by a high electronegativity instead of a high collision frequency have been identified.

14:30
KW2 4 Modeling of the filamentary plasma generated in an rf plasma jet at atmospheric pressure* F. SIGENEGER, J.

SCHÄFER, R. FOEST, K.-D. WELTMANN, D. LOFFHAGEN, *INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* The argon plasma occurring in an rf plasma jet at atmospheric pressure is investigated by a two-dimensional fluid model. The jet consists of two concentric capillaries and two ring-shaped electrodes which are twisted around the outer capillary with a gap of 4 mm. The plasma is sustained by an rf voltage at 27.12 MHz which is supplied to the upper electrode. The lower electrode is grounded. The axisymmetric model comprises continuity equations for electrons and the most important argon species, the electron energy balance equation, Poisson's equation and an equation for the surface charges at the walls of the capillaries. Furthermore, the heat balance equation is solved to determine the temperature of the gas. The transport properties of electrons and the collision rate coefficients have been determined by solving the electron Boltzmann equation as functions of the electron mean energy and of the ionization degree. The results show a distinct separation between the bulk plasma in the center between the inner and outer capillaries and the sheath regions in front of the electrodes.

14:45
KW2 5 Evaluation of RF Micro-Discharge Regimes in the Performance of Evanescent-Mode Cavity Resonators* ABBAS SEMNANI, DIMITRIOS PEROULIS, *Purdue University* A number of different RF discharge mechanisms may be important in gas breakdown including ionization, secondary electron emission, and field emission.[†] However, the impact of each of these mechanisms is a strong function of frequency.[‡] Consequently, estimating power handling in microwave devices needs to carefully consider the operating frequency. In this paper, we study the frequency-dependent impact of these mechanisms in two evanescent-mode cavity resonators[§] operating at 1 GHz and 50 GHz. The key characteristic of these resonators, unlike typical cavities, is that the resonant electric field is primarily concentrated in a relatively small volume. The smallest dimension of this volume is referred to as critical gap and typically is in the order of a few μm. The two resonators in this study have the same critical gap size of 19 μm which results in the same gas critical frequency of 6.3 GHz in atmospheric pressure. Plasma simulation results as well as the electromagnetic simulations considering plasma are presented and compared for both cases which operate in different discharge mechanisms.

[†]A. Semnani *et al.,* Appl. Phys. Lett., **102**, 174102 (2013).
[‡]C. E. Muehe, DTIC Document, (1965).
[§]K. Chen *et al.,* International Microw. Symp., (2013).

SESSION KW3: GREEN PLASMA TECHNOLOGIES II
Wednesday Afternoon, 2 October 2013; Room: Nassau Room at 13:30; Biswa Ganguly, Air Force Research Laboratory, presiding

Invited Papers

13:30
KW3 1 Developments in Power efficient dissociation of CO2 using non-equilibrium plasma activation RICHARD VAN DE SANDEN, *Dutch Institute for Fundamental Energy Research*

Sustainable energy generation by means of, either photovoltaic conversion, concentrated solar power or wind, will certainly form a significant part of the energy mix in 2025. The intermittency as well as the temporal variation and the regional

spread of this energy source, however, requires a means to store and transport energy on a large scale. In this presentation the means of storage will be addressed of sustainable energy transformed into fuels and the prominent role plasma science and technology can play in this great challenge. The storage of sustainable energy in these so called solar fuels, e.g. hydrocarbons and alcohols, by means of artificial photosynthesis from the feedstock CO2 and H2O, will enable a CO2 neutral power generation infrastructure, which is close to the present infrastructure based on fossil fuels. The challenge will be to achieve power efficient dissociation of CO2 or H2O or both, after which traditional chemical conversion (Fisher-Tropsch, Sabatier, etc.) towards fuels can take place. A promising route is the dissociation or activation of CO2 by means of plasma, possible combined with catalysis. Taking advantage of non-equilibrium plasma conditions to reach optimal energy efficiency we have started a solar fuels program at the beginning of 2012 focusing on CO2 plasma dissociation into CO and O2. The plasma is generated in a low loss microwave cavity with microwave powers up to 10 kW using a supersonic expansion to quench the plasma and prevent vibrational-translational relaxation losses. New ideas on the design of the facility and results on power efficient conversion (more then 50%) of large CO2 flows (up to 75 standard liter per minute with 11% conversion) at low gas temperatures will be presented.

Contributed Papers

14:00

KW3 2 Production of Nano-composite Si-M powders by plasma spraying for next generation lithium ion batteries* MAKOTO KAMBARA, NAREN GERILE, MASHIRO KAGA, TASUKU HIDESHIMA, *Dept. Mater. Eng., The University of Tokyo* DEPT. MATER. ENG., THE UNIVERSITY OF TOKYO TEAM   We have attempted plasma spraying to produce nano Si powders for lithium ion batteries at the industrial compatible throughputs. Several 100 nm nano-composite powders are typically produced from metallurgical grade Si powders, and its improved battery capacity has been revealed. When doped with >10 mol%Ni, several SiNix alloy particles, that are the congruent phases with relatively high melting temperature in the Si-Ni binary system, were produced. The battery performance of these powders was not as good as that with Si powders only. In contrast, at 5 mol%Ni addition, NiSi$_2$ phase was only detected apart from Si. Importantly, the battery performance was improved. Since NiSi$_2$ is an incongruent phase that forms through peritectic reaction, it plausibly nucleates heterogeneously on surface of Si particles that nucleate in advance. In fact, TEM analysis revealed that NiSi$_2$ was present on Si surface not as individual particles. Therefore, such a composite structure, not a simple mixture of foreign particles, is considered to improve the battery performance possibly by increasing the particle mechanical integrity as well as the electric conductivity of the electrode.

*This work was partly supported by the Funding Program for Next Generation World-Leading Researchers (NEXT Program) of Japan.

14:15

KW3 3 Planar NO LIF measurement of point-to-plane discharge in a premixed propane/air flame JACOB SCHMIDT, *Spectral Energies, LLC*. BISWA GANGULY, *Air Force Research Laboratory*   The effect of a point-to-plane pulsed discharge induced radical production in a pre-mixed propane/air flame has been investigated by phase-locked Planar Laser-Induced-Fluorescence (PLIF) measurements of NO radical. NO fluorescence images were acquired by exciting transitions within the A2Σ+ ← X2Π (v' = v'' = 0) γ -band, near 226 nm. Phase locked NO PLIF measurements with the variation of pulsed plasma energy, equivalence ratio, applied voltage rise time have been performed. A fast rise time (20 ns) and a slower rise time (250 ns), 8-10 kV high voltage pulsers are used to produce NO radical densities 10-100 times greater than the ambient flame produced NO radicals in both lean, balanced and rich pre-mixed flames with ⩽ 2.5 mJ deposited pulsed energy per pulse. The excess NO radical densities were found to decay to 50%

level with time constants ⩾250 μs in the burnt gas regions with gas temperatures greater than 1000 K. The super-equilibrium NO populations were dependent on the deposited energy and overall equivalence ratio, but independent of pulse rise time for similar energy deposition per pulse. Due to long decay lifetimes, super-equilibrium NO populations are convected away with the ambient flow from plasma production regions in the flame and observed in downstream exhaust gas regions.

14:30

KW3 4 Measurement of OH radical density in DBD-enhanced premixed burner flame by laser-induced fluorescence KAZUNORI ZAIMA, KOICHI SASAKI, *Hokkaido Univ.*   We examined OH density in DBD-enhanced premixed burner flame by laser-induced fluorescence (LIF). We ignited a premixed flame with $CH_4/O_2/Ar$ mixture using a burner which worked as the ground electrode. The upper part of the flame was covered with a quartz tube, and we attached an aluminum electrode on the outside of the quartz tube. DBD inside the quartz tube was obtained between the aluminum electrode and the burner nozzle. The planar beam from a pulsed tunable laser excited OH in, and we captured two-dimensional distribution of the LIF intensity using an ICCD camera. We employed three pump lines of Q_1(J=4, 8 and 10), and the rotational temperature of OH(X) was deduced from the ratio of the LIF intensities. The total density of OH was obtained from the LIF intensities and the rotational temperature. A principal experimental result was that no remarkable increase was observed in the OH density by the superposition of DBD. The correlation between the pulsed discharge current and the temporal variation of the OH density was not clear, suggesting that the oscillation of the OH density with a small amplitude is related to the transittion time constant between equilibrium and nonequilibrium combustion chemistries.

14:45

KW3 5 Microwave plasma jet assisted combustion of premixed methane-air: Roles of OH(A) and OH(X) radicals* CHUJI WANG, WEI WU, *Mississippi State University*   Plasma assisted combustion (PAC) technology can enhance combustion performance by pre-heating combustion fuels, shortening ignition delay time, enhancing flame holding, or increasing flame volume and flame speed. PAC can also increase fuel efficiency by extending fuel lean flammability limit (LFL) and help reduce combustion pollutant emissions. Experiment results have shown that microwave plasma could modify flame structure, increase flame volume, flame speed, flame temperature, and flame stability, and could also extend the fuel lean flammability limit. We report on a novel microwave PAC system that allows us to study PAC using complicated yet

well-controlled combinations of operating parameters, such as fuel equivalence ratio (φ), fuel mixture flow rate, plasma gas flow rate, plasma gases, plasma jet configurations, symmetric or asymmetric fuel-oxidant injection patterns, etc. We have investigated the roles of the stated-resolved OH(A, X) radicals in plasma assisted ignition and combustion of premixed methane-air fuel mixtures. Results suggest that that both the electronically excited state OH(A) and the electronic ground state OH(X) enhance the methane-air ignition process, i.e. extending the fuel LFL, but the flame stabilization and flame holding is primarily determined by the electronic ground state OH(X) as compared to the role of the OH(A). E-mail: cw175@msstate.edu.

SESSION KW5: ELECTRON AND POSITRON COLLISIONS WITH ATOMS
Wednesday Afternoon, 2 October 2013; Room: Village Square at 13:30; Klaus Bartschat, Drake University, presiding

Invited Papers

13:30
KW5 1 Positron collisions from simple atoms and positronium-hydrogen collisions*
S.J. WARD, *University of North Texas*

I plan to present calculations of three-body, effective three-body and four-body collisions at low energies that involve a positron. We applied the hyperspherical hidden crossing method with a correction term to Ps formation in low energy e^+-H [1,2], e^+-Li [2,3,4] and e^+-Na collisions [2]. We considered the alkali atoms Li and Na as effective one-electron atoms, so that e^+-Li collisions and e^+-Na collisions can be considered as effective three-body collisions. The calculations provide an explanation of the extremely small S-wave Ps formation cross section for e^+-H, e^+-Li and e^+-Na collisions in terms of destructive interference. The S-wave cross section for Ps formation in e^+-Li and in e^+-Na collisions increases with decreasing momentum of the incoming Ps, which is consistent with the Wigner threshold law [5]. We have also studied at low-energies a fundamental four-body Coulomb process, that of elastic Ps-H scattering [6]. Using the Kohn variational method (and variants of this method) we have computed accurate ^{1,3}S- and ^{1,3}P-wave phase shifts. We also have some preliminary ^{1,3}D-wave phase shifts.

[1] S. J. Ward, J. H. Macek, and S. Yu. Ovchinnikov, Phys. Rev. A **59**, 4418 (1999).
[2] S. J. Ward and J. Shertzer, New. J. Phys. **14**, 025003 (2012).
[3] S. J. Ward and J. Shertzer, Phys. Rev. A **68**, 032720 (2003).
[4] S. J. Ward, J. Shertzer, S. Yu. Ovchinnikov, and J. H. Macek, Phys. Rev. A **75**, 012713 (2007).
[5] P. Wigner, Phys. Rev. **73**, 1002 (1948).
[6] Denton Woods, S. J. Ward, and P. Van Reeth, Bull. Am. Phys. Soc. **58**, no. 6, p. 175 (2013).

Contributed Papers

14:00
KW5 2 Rearrangement processes in low-energy positron scattering on hydrogen and the alkali metals* IGOR BRAY, A.V. LUGOVSKOY, A.S. KADYROV, *Curtin University* We apply the two-center convergent close-coupling (CCC) method to the calculation of low-energy positron scattering on atomic hydrogen and the alkali metals. Our primary interest is in the near-threshold exothermic rearrangement processes. Examples include positronium (Ps) formation for the alkali metals at near-zero positron energy, and (anti)hydrogen formation in near-threshold Ps-(anti)proton scattering. The cross sections for such processes are infinite at threshold, and we investigate their behavior in the vicinity of threshold.

14:15
KW5 3 A simple approach to calculating positronium formation ALLAN STAUFFER, *Department of Physics and Astronomy, York University, Toronto, Canada* ROBERT MCEACHRAN, *CAMS, Research School of Physics and Engineering, Australian National University, Canberra, Australia* We have developed a simple method to calculate positronium formation in positron-atom scattering based on an idea first proposed by Reid and Wadehra [1]. We have applied it to positron scattering from neon, argon, krypton and xenon. Our method involves lowering the threshold for direct ionization, I, by 6.8 eV, the binding energy of positronium, and calculating the ionization cross section using our complex optical potential approach [2]. By subtracting the cross section for ionization calculated with the unmodified threshold for ionization we obtain the result for positronium formation. Since the positronium formation cross section goes to zero more rapidly than for direct ionization, we have taken this into account by linearly raising the threshold for ionization until it coincides with I for incident positron energies above 120 eV. We have found that our cross sections calculated this way are in better overall agreement with experimental measurements than more elaborate theoretical calculations.

[1] D.D. Reid and J.M. Wadehra 1996 J. Phys. B **29** L127.
[2] R.P. McEachran and A.D. Stauffer, 2013 J. Phys. B **46** 03.

Invited Papers

14:30

KW5 4 Electron Impact Single and Double Ionization of Helium calculated with Generalized Sturmian Functions
DARIO MITNIK,* *IAFE and UBA, Argentina*

The single and double ionization of He induced by the collision of high incident energy electrons still remains a challenging problem for theoreticians. Several ab initio calculations (see [1]) of excitation-ionization disagree which each other and with the experimental data [2]. A similar situation is found for the double ionization of He [3]. In this talk, we will provide cross sections for both processes calculated by using the Generalized Sturmian Functions method [4,5]. Comparisons with experimental data [6] and with other calculations will be presented.

*M.J. Ambrosio, G. Gasaneo, and A.I. Gomez, UNS, Argentina, and L.U. Ancarani, UL, France.

[1] J. M. Ngoko Djiokap *et al.*, Phys. Rev. A **81**, 042712 (2010).
[2] C. Dupre *et al.*, J. Phys. B **25**, 259 (1992).
[3] L. U. Ancarani *et al.*, J. Phys.: Conf. Ser **212**, 012025 (2010).
[4] D M Mitnik *et al.*, Comp. Phys. Comm. **182**, 1145 (2011).
[5] G. Gasaneo *et al.*, Accepted in Adv. Quantum Chem. (2013).
[6] A Lahmam-Bennani *et al.*, J. Phys. B **42**, 165201 (1999); A. Kheifets *et al.*, J. Phys. B **32**, 5047 (1999).

SESSION LW1: PLASMA ETCHING
Wednesday Afternoon, 2 October 2013; Room: Ballroom I at 15:30; Vincent Donnelly, University of Houston, presiding

Invited Papers

15:30

LW1 1 Challenges in the Plasma Etch Process Development in the sub-20nm Technology Nodes
KAUSHIK KUMAR, *TEL Technology Center, America, LLC*

For multiple generations of semiconductor technologies, RF plasmas have provided a reliable platform for critical and non-critical patterning applications. The electron temperature of processes in a RF plasma is typically several electron volts. A substantial portion of the electron population is within the energy range accessible for different types of electron collision processes, such as electron collision dissociation and dissociative electron attachment. When these electron processes occur within a small distance above the wafer, the neutral species, radicals and excited molecules, generated from these processes take part in etching reactions impacting selectivity, ARDE and micro-loading. The introduction of finFET devices at 22 nm technology node at Intel marks the transition of planar devices to 3-dimensional devices, which add to the challenges to etch process in fabricating such devices. In the sub-32 nm technology node, Back-end-of-the-line made a change with the implementation of Trench First Metal Hard Mask (TFMHM) integration scheme, which has hence gained traction and become the preferred integration of low-k materials for BEOL. This integration scheme also enables Self-Aligned Via (SAV) patterning which prevents via CD growth and confines via by line trenches to better control via to line spacing. In addition to this, lack of scaling of 193 nm Lithography and non-availability of EUV based lithography beyond concept, has placed focus on novel multiple patterning schemes. This added complexity has resulted in multiple etch schemes to enable technology scaling below 80 nm Pitches, as shown by the memory manufacturers. Double-Patterning and Quad-Patterning have become increasingly used techniques to achieve 64 nm, 56 nm and 45 nm Pitch technologies in Back-end-of-the-line. Challenges associated in the plasma etching of these multiple integration schemes will be discussed in the presentation. In collaboration with A. Ranjan, TEL Technology Center, America, LLC, 255 Fuller Rd., Suite 244, Albany, New York, 12203.

Contributed Papers

16:00

LW1 2 Photo-assisted etching of silicon in halogen-containing plasmas* SHYAM SRIDHAR, WEIYE ZHU, LEI LIU, DEMETRE ECONOMOU, VINCENT DONNELLY, *University of Houston* Cl_2, Br_2, HBr, and HBr/Cl_2 feed gases diluted in Ar were used to study etching of p-type Si(100) in a RF inductively coupled, Faraday-shielded plasma. Etching rates were measured as a function of ion energy. Etching at ion energies below the threshold for ion-assisted etching was observed in all cases, with Br_2/Ar and HBr/Cl_2/Ar plasmas having the lowest and highest sub-threshold etching rates, respectively. Sub-threshold etching rates scaled with the product of surface halogen coverage (measured by XPS) and Ar emission intensity (7504Å). Etching rates measured under MgF_2, quartz, and opaque windows, or biased grids, showed that sub-threshold etching is due to photon-stimulated processes on the surface, with VUV photons being much more effective than longer wavelengths. Scanning electron and atomic force microscopy (SEM and AFM) revealed that photo-etched surfaces were very rough, quite likely due to the inability of the photo-assisted process to remove contaminants from the surface. Photo-assisted etching in Cl_2/Ar plasmas resulted in the formation of 4-sided pyramidal features with bases that form an angle of 45° with respect to (110).

cleavage planes, suggesting that the photo-assisted etching process is sensitive to crystal orientation, at least for chlorine.

16:15

LW1 3 Effect of TCP Pulsing in Photon Induced Sub-threshold Etching of Si JULINE SHOEB, SARAVANAPRIYAN SRIRAMAN, TOM KAMP, ALEX PATERSON, *Lam Research Corporation* With decrease in device sizes, plasma damage minimization of Si becomes very important. During over-etch processes a passivation layer protects Si from ions. Even below etching threshold energy, UV photons can cleave Si-Si bonds that acts as a precursor for Si etching. In HBr/He/O_2 plasmas, 58.4nm photons from He(2^1p) and 130nm photons from O(3s) can result in sub-threshold etching of Si by Si-Si bond cleaving followed by Si etching as volatile $SiBr_4$.*Literature reports reduction in UV damage with ICP power pulsing.[†] During pulse-off period, electron temperature drops thereby reducing meta-stable densities responsible for photon emission. Reducing radical and ion density and photon fluxes, pulsed plasmas possibly can reduce sub-threshold Si etching.[‡] In this talk, a comparison of sub-threshold damage of Si between continuous and pulsed HBr/He/O_2 plasmas using modeling and experiments will be presented.

*J. Shoeb, S. Sriraman, T. Kamp, and A. Paterson, 65th GEC, Austin TX, (2012).

[†]C. P. Etienne *et al.*, J. Vac. Sci. Technol. B **31**(1), (2012).

[‡]Ibid.

16:30

LW1 4 Vacuum ultraviolet photon fluxes in argon-containing inductively coupled plasmas* S.B. RADOVANOV, H.M. PERSING, *Applied Materials, Silicon Systems Group, Varian Semiconductor Equipment* S. WANG, C.L. CULVER, J.B. BOFFARD, C.C. LIN, A.E. WENDT, *University of Wisconsin-Madison* Vacuum ultraviolet (VUV) photons emitted from excited atomic states are ubiquitous in material processing plasmas. Damage of materials is induced by energy transfer from the VUV photons to the surface, causing disorder in the surface region, surface reactions, and affecting bonds in the material bulk. Monitoring of the surface flux of VUV photons from inductively coupled plasmas (ICP) and its dependence on discharge parameters is thus highly desirable. Results of non-invasive, direct windowless VUV detection using a photosensitive diode will be presented. Relative VUV fluxes were also obtained using a sodium salicylate coating on the inside of a vacuum window, converting VUV into visible light detected through the vacuum window. The coating is sensitive to wavelengths in the range 80-300 nm, while the photodiode is only sensitive to wavelengths below 120 nm. In argon the VUV emissions are primarily produced by spontaneous decay from $3p^54s$ resonance levels ($1s_2,1s_4$) and may be reabsorbed by ground state atoms. Real-time resonance level concentrations were measured [1] and used to predict the VUV photon flux at the detector for a range of different ICP pressures, powers, and for various admixtures of Ar with N_2, and H_2.

[1]JVSTA **31** (2013), 021303.

16:45

LW1 5 Reduction Mechanism of Surface Roughness on ArF-Photoresist Using C_5HF_7 Gas Plasma YUDAI MIYAWAKI, KEIGO TAKEDA, HIROKI KONDO, KENJI ISHIKAWA, MAKOTO SEKINE, *Nagoya University* AZUMI ITO, HIROKAZU MATSUMOTO, *ZEON CORPORATIO* MASARU HORI, *Nagoya University* Fluorocarbon (FC) plasmas have been used in reactive ion etch processes for the fabrication of high-aspect-ratio-contact-hole on SiO_2. There are some needs, such as high selectivity over photoresist (PR), Si_3N_4 and Si, avoiding surface roughness formation on ArF- PR. C_5F_8 gas is known to improve the SiO_2 selectivity compared with C_4F_8 and conventional gas chemistries. Recently, we achieved that highly selective etching of SiO_2 against PR, Si_3N_4 and Si using a newly-designed gas, C_5HF_7, and O_2, Ar gas mixture. So far, we have investigated the etch performances and its mechanism using C_5HF_7 gas chemistry through comparison with C_5F_8 gas. In this study, we focused on the mechanism of reducing the surface roughness formation on ArF-PR during SiO_2 etching in the C_5HF_7 gas chemistry. The plasma etching time dependency of surface morphology on ArF-PR was compared with the case of C_5F_8. For C_5F_8/O_2/Ar plasma, surface roughness increased. For C_5HF_7/O_2/Ar plasma, RMS roughness about 2 nm was formed on the PR surface at 5 sec. As the time elapsing, surface roughness stayed constant. The RMS roughness caused by C_5HF_7 gas chemistry was lower than that of C_5F_8. Since F atoms in FC film were reduced by hydrofluorocarbon species, C_xHF_y, the FC polymerization was enhanced selectively on PR to form a thicker FC film that protects the PR surface from ion bombardments, while keeping the high etch rate for SiO_2.

17:00

LW1 6 Molecular Dynamics Analysis of Surface Reaction Kinetics during Si Etching in Cl-based Plasmas: Effects of Etch By-Products Ion Incidence NOBUYA NAKAZAKI, YOSHINORI TAKAO, KOJI ERIGUCHI, KOUICHI ONO, *Department of Aeronautics and Astronautics, Graduate School of Engineering, Kyoto University* Profile anomalies and surface roughness are critical issues to be resolved in plasma etching of nanometer-scale microelectronic devices, which in turn requires a better understanding of the effects of ion incident energy and angle on surface reaction kinetics. This paper presents a classical molecular dynamics (MD) simulation of Si etching by energetic Cl^+ and $SiCl_x^+$ ($x = 1$–4) ion beams at normal incidence with different energies $E_i = 20$–500 eV, where the improved Stillinger-Weber interatomic potential was used for Si/Cl system. Emphasis is placed on differences in the etching mechanisms between the etchant and etch by-products ion incidences. Numerical results indicated that in Cl^+ incidence, the Si etch yield increases with increasing E_i; on the other hand, in $SiCl^+$ incidence, the deposition of Si atoms (or minus Si etch yield) occurs at lower $E_i \leqslant 300$ eV while the etching occurs at high $E_i > 300$ eV. In addition, in Cl^+ incidence, the thickness of surface reaction layers and the coverage (or concentration) of Cl atoms therein increase with increasing E_i, while in $SiCl^+$ incidence, the surface layer thickness and the Cl coverage are large at lower E_i owing to deposition.

17:15

LW1 7 Simulation of microwave pulsing in a radial line slot antenna etch process reactor ROCHAN UPADHYAY, *Esgee Technologies Inc.* KIYOTAKA ISHIBASHI, *Tokyo Electron Limited* LAXMINARAYAN RAJA, *The University of Texas at Austin* The radial line slot antenna reactor couples the microwave power to a process plasma through a slot antenna. This arrangement leads to efficient generation of plasma with high electron energy adjacent to the window and a lower energy near wafer surfaces. This arrangement is beneficial for low ion energy applications such as soft etching or thin film processing. With increased charge

densities, charge-up damage of dielectric surfaces can be a problem that can be addressed though plasma pulsing strategies in electronegative feed gases. The periodic power-off cycle results in an afterglow where electron attachment forms large amounts of negative ions that when extracted to the wafer surface, reduces the effects of positive charge trapping on the surface. We use computational modeling to investigate the effect of microwave pulsing on the negative ion generation rates for high density HBr and CF4 plasmas. We discuss improvements to a plasma chemistry mechanism for the pulsed plasma regime. Our results verify much larger negative ion to electron density ratios compared to the continuous (un-pulsed) case for both HBr and CF4 gases. Results also indicate greater plasma uniformity due to diffusion of positive and negative ions during the power-off phase of the pulse.

SESSION LW2: PLASMA MODELLING I
Wednesday Afternoon, 2 October 2013; Room: Ballroom II at 15:30; Vladimir Kolobov, University of Alabama, presiding

Invited Papers

15:30
LW2 1 Particle based discharge simulations: electron heating and electromagnetic effects*
THOMAS MUSSENBROCK, *Ruhr University Bochum*

It is widely acknowledged that kinetic effects play a significant role in almost all kinds of technological plasmas. These plasmas often exhibit several groups of electrons with significantly different energies. The intrinsically non-Maxwellian behavior of the electron energy distribution function in this case invalidates fluid-based simulation approaches, so that a self-consistent kinetic treatment is needed to capture all important physics features. This holds in particular for the heating of electrons. The situation becomes even more complicated if in addition to the kinetic treatment electromagnetic effects have to be considered. This is for example the case when the electrode size and driving frequency of capacitive discharges increase. In this contribution we discuss how electromagnetic models based on the Darwin approximation of Maxwell's equations can be incorporated into kinetic simulations of technological plasmas to meet the goals of scientific accuracy and computational efficiency.

Contributed Papers

16:00
LW2 2 Fluid modeling of low-temperature plasma transport across a magnetic field* R. FUTTERSACK, G.J.M. HAGELAAR, *LAPLACE, University of Toulouse, France* P. TAMAIN, A. SIMONIN, *CEA, IRFM, France* While various low-temperature plasma sources operating with a steady magnetic field are widely used in industrial and research applications, the knowledge of magnetized transport in these plasmas is still incomplete. As the transport of charges and currents in such plasma sources may show a complex and ill-understood behavior, we investigate the issue of magnetized transport as such. A new 2D fluid model has been developed, combining the usual methods of low-temperature plasma modeling with techniques drawn from fusion plasmas research, and therefore allowing to explore a large range of magnetic field strengths and topologies. We then analyze simulations related to representative experiments with various magnetic field configurations in order to characterize the transport in these low-temperature plasmas, and compare the results with experimental data and application-oriented models. For two different negative ion sources, the main behavior of the plasma is recovered, with the emergence of asymmetries due to the drifts induced by the magnetic field. The model is also able to capture the transient dynamics of the plasma such as certain types of instabilities.

16:15
LW2 3 An External Circuit Model for 3D Electromagnetic Particle-In-Cell Simulations* MING-CHIEH LIN, CHUAN-DONG ZHOU, DAVID N. SMITHE, *Tech-X Corporation* GYROPIC TEAM In this work, an algorithm for coupling external circuit elements to electromagnetic (EM) particle-in-cell (PIC) simulations is developed. The circuit equation including an external voltage or current source, resistance, inductance, capacitance, and a dynamic load is solved simultaneously with the EM PIC updaters through an instant measured voltage across the system to obtain the supplied current for feeding into the system. This external circuit model has been demonstrated and implemented in a 3D conformal finite-difference time-domain PIC code, Vorpal.

16:30
LW2 4 PumpKin: A tool to find principal pathways in plasma chemical models* ARAM H. MARKOSYAN, *CWI, Amsterdam, The Netherlands* ALEJANDRO LUQUE, FRANCISCO J. GORDILLO VÁZQUEZ, *Instituto de Astrofsica de Andaluca (IAA CSIC), Spain* UTE EBERT, *CWI, Amsterdam, The Netherlands* Recent kinetic models of atmospheric chemistry or of many industrial processes contain thousands of chemical reactions and species. The reactions depend on timescales, electric fields, temperature, pressure etc. We have developed a software tool called PumpKin

(pathway reduction method for plasma kinetic models) to find all principal pathways in such complex plasma chemistry models, i.e. the dominant reaction sequences. PumpKin is a universal tool, inspired by [Lehmann, *J Atmos Chem* **41**, 297 (2002)]. It requires to define and to run once a complete plasma kinetics solver, e.g. ZDPlasKin [http://www.zdplaskin.laplace.univ-tlse.fr], up to the time of interest. The stoichiometric matrix of the system, the reaction rates and the temporal profile of the species densities are the input for PumpKin to systematically identify the principal pathways.

16:45
LW2 5 Arbitrarily high-order semi-Lagrangian methods for the kinetic description of plasmas YAMAN GÜÇLÜ, ANDREW J. CHRISTLIEB, *Michigan State University* WILLIAM N.G. HITCHON, *University of Wisconsin-Madison* In the kinetic description of low-temperature plasmas, deterministic mesh-based solvers excel for their capacity to resolve small electric fields in quasi-neutral regions, and to compute accurate ionization rates involving a small population of high energy electrons. Among these, semi-Lagrangian methods like the Convected Scheme (CS) are preferred, because of their ability to take large time-steps (no CFL limit) and their low numerical diffusion. The CS is mass conservative and positivity preserving, and was recently extended to arbitrarily high order of accuracy in phase-space [1,2]: the new scheme was applied to the Vlasov-Poisson system on periodic domains, and validated against classical 1D-1V test-cases. Here we introduce the effect of scattering collisions and wall recombination, include kinetic ions, and extend the model to 1D-2V. We investigate the formation of a planar presheath, and compare the new results to low-order simulations.

[1] Y. Güçlü, A.J. Christlieb and W.N.G. Hitchon, "High order semi-Lagrangian schemes and operator splitting for the Boltzmann equation." ICERM, June 3-7 2013. https://icerm.brown.edu/tw13-1-isbeaa.
[2] ——, "Arbitrarily high-order Convected Scheme solution of the Vlasov-Poisson system." Submitted to J. Comput. Phys., July 2013.

17:00
LW2 6 A hybrid model to estimate particle fluxes in a fluid mode using a particle-in-cell Monte Carlo collision method* SEOK WON HWANG, HO-JUN LEE, HAE JUNE LEE, *Department of Electrical Engineering, Pusan National University* Fluid models have been widely used in plasma simulations and conducted successfully under near-atmospheric pressure conditions such as plasma display panels and atmosphere pressure plasma devices. However, fluid models have drawbacks in low pressure conditions because they cannot describe exact energy distribution of species in spatial and temporal domains. As a result, fluid models are not able to calculate the transport and the reaction coefficients, nor represent non-local effects at low pressure. In order to minimize these, the Monte Carlo collision (MCC) methods have been additionally used to obtain the energy distribution function of each species, especially for electrons in conventional hybrid models. Another problem in conventional fluid models is to utilize a drift-diffusion approximation (DDA) for transport fluxes for electrons and ions instead of the momentum conservation equation. However, if DDA is used at low pressure, the flux is overestimated because the approximation assumes the instant local balanced steady state from collisions. In this work, a new hybrid method is introduced to provide the correct flux using particle-in-cell (PIC) coupled with MCC instead of DDA. The results of the modified hybrid simulation show better agreement with a full PIC simulation. In addition, the effect of boundary conditions on the potential and density distribution is investigated.

17:15
LW2 7 Automatic Coarsening of the Particle Interaction Mesh in a Hybrid PIC-DSMC Simulation STAN MOORE, PAUL CROZIER, CHRIS MOORE, MATTHEW BETTENCOURT, MATTHEW HOPKINS, *Sandia National Laboratories* Hybrid particle-in-cell (PIC) and direct simulation Monte Carlo (DSMC) methods are frequently used to simulate low density interacting plasmas, and a single mesh is often used for both DSMC and PIC calculations. Typically however, the mesh size for the PIC method is limited by the Debye length, while the particle interaction mesh in DSMC is limited by the mean free path, which is often much larger than the Debye length. Insufficient computational particles in a DSMC collision cell can also lead to spurious results when using the no-time-counter scheme. Therefore, the optimal PIC mesh may be suboptimal for calculating DSMC collisions. We have developed a method where a finer unstructured tetrahedral mesh is used for PIC calculations, and a coarser conglomeration of PIC mesh elements is used by the DSMC algorithm to calculate particle interactions (i.e. elastic collisions, ionizations, etc.). This automatic coarsening of the PIC elements into DSMC interaction cells is accomplished using an oct-tree algorithm, based on the mean free path calculated using the previously simulated local collision rate. Using two different sized meshes for PIC vs. DSMC gives greater flexibility to the simulation and allows one to reduce the computational cost by using fewer computational particles while still accurately simulating the DSMC collisions. The new method is demonstrated and results and computational speed are compared to the traditional hybrid PIC-DSMC simulation method.

SESSION LW3: BIOMEDICAL APPLICATIONS I
Wednesday Afternoon, 2 October 2013; Room: Nassau Room at 15:30; Alexander Fridman, Drexel University, presiding

Invited Papers

15:30
LW3 1 Physics and medical applications of cold atmospheric plasma MICHAEL KEIDAR, *George Washington University*

Recent progress in atmospheric plasmas led to the creation of cold plasmas with ion temperature close to room temperature. Varieties of novel plasma diagnostic techniques were applied in a quest to understand physics of cold plasmas. In particular it was established that the streamer head charge is about 10^8 electrons, the electrical field in the head vicinity is about 10^7 V/m, and the electron density of the streamer column is about 10^{19} m^3. We have demonstrated the efficacy of cold plasma in a pre-clinical model of various cancer types (lung, bladder, breast, head, neck, brain and skin). Both *in-vitro* and *in-vivo* studies revealed that cold plasmas selectively kill cancer cells. We showed that: (a) cold plasma application selectively eradicates cancer cells in vitro without damaging normal cells. (b) Significantly reduced tumor size *in vivo*. Cold plasma treatment led to tumor ablation with neighbouring tumors unaffected. These experiments were performed on more than 10 mice with the same outcome. We found that tumors of about 5mm in diameter were ablated after 2 min of single time plasma treatment. The two best known cold plasma effects, plasma-induced apoptosis and the decrease of cell migration velocity can have important implications in cancer treatment by localizing the affected area of the tissue and by decreasing metastasic development. In addition, cold plasma treatment has affected the cell cycle of cancer cells. In particular, cold plasma induces a 2-fold increase in cells at the G2/M-checkpoint in both papilloma and carcinoma cells at $\sim$24 hours after treatment, while normal epithelial cells (WTK) did not show significant differences. It was shown that reactive oxygen species metabolism and oxidative stress responsive genes are deregulated. We investigated the production of reactive oxygen species (ROS) with cold plasma treatment as a potential mechanism for the tumor ablation observed.

Contributed Papers

16:00
LW3 2 Gene Transfection Method Using Atmospheric Pressure Dielectric-Barrier Discharge Plasmas SHOTA SASAKI, MAKOTO KANZAKI, TOSHIRO KANEKO, *Department of Electronic Engineering, Tohoku University.* Gene transfection which is the process of deliberately introducing nucleic acids into cells is expected to play an important role in medical treatment because the process is necessary for gene therapy and creation of induced pluripotent stem (iPS) cells. However, the conventional transfection methods have some problems, so we focus attention on promising transfection methods by atmospheric pressure dielectric-barrier discharge (AP-DBD) plasmas. AP-DBD He plasmas are irradiated to the living cell covered with genes. Preliminarily, we use fluorescent dye YOYO-1 instead of the genes and use LIVE/DEAD Stain for cell viability test, and we analyze the transfection efficiency and cell viability under the various conditions. It is clarified that the transfection efficiency is strongly dependence on the plasma irradiation time and cell viability rates is high rates (>90%) regardless of long plasma irradiation time. These results suggest that ROS (Reactive Oxygen Species) and electric field generated by the plasma affect the gene transfection. In addition to this (the plasma irradiation time) dependency, we now investigate the effect of the plasma irradiation under the various conditions.

16:15
LW3 3 Plasma-activated medium induced apoptosis on tumor cells MASARU HORI, HIROMASA TANAKA, MASAAKI MIZUNO, KAE NAKAMURA, HIROAKI KAJIYAMA, KEIGO TAKEDA, KENJI ISHIKAWA, HIROYUKI KANO, FUMITAKA KIKKAWA, *Nagoya University.* The non-equilibrium atmospheric pressure plasma (NEAPP) has attracted attention in cancer therapy. In this study, the fresh medium was treated with our developed NEAPP, ultra-high electron density (approximately 2×10^{16} cm^{-3}) [1,2]. The medium called the plasma-activated medium (PAM) killed not normal cells but tumor cells through induction of apoptosis. Cell proliferation assays showed that the tumor cells were selectively killed by the PAM. Those cells induced apoptosis using an apoptotic molecular marker, cleaved Caspase3/7. The molecular mechanisms of PAM-mediated apoptosis in the tumor cells were also found that the PAM downregulated the expression of AKT kinase, a marker molecule in a survival signal transduction pathway. These results suggest that PAM may be a promising tool for tumor therapy by downregulating the survival signals in cancers.

[1] M. Iwasaki *et al.* Appl. Phys. Lett. **92**, 081503 (2008).

[2] H. Tanaka *et al.* Plasma Medicine 1(3-4) 265-277 (2011).

16:30
LW3 4 DNA damage in oral cancer cells induced by nitrogen atmospheric pressure plasma jets XU HAN, MATEJ KLAS, YUEYING LIU, M. SHARON STACK, SYLWIA PTASINSKA, *University of Notre Dame.* The nitrogen atmospheric pressure plasma jet (APPJ) has been shown to effectively induce DNA double strand breaks in SCC-25 oral cancer cells. The APPJ source constructed in our laboratory consists of two external electrodes wrapping around a quartz tube and nitrogen as a feed gas and operates based on dielectric barrier gas discharge. Generally, it is more challenging to ignite plasma in N2 atmosphere than in noble gases. However, this design provides additional advantages such as lower costs compared to the noble gases for future clinical operation. Different parameters of the APPJ configuration were tested in order to determine radiation dosage. To explore the effects of delayed damage and cell self-repairing, various incubation times of cells after plasma treatment were also performed. Reactive species generated in plasma jet and in liquid environment are essential to be identified and quantified, with the aim of unfolding the mystery of detailed mechanisms for plasma-induced cell apoptosis. Moreover, from the comparison of plasma treatment effect on normal oral cells OKF6T, an insight to the selectivity for cancer treatment by APPJ can be explored. All of these studies are critical to better understand the damage responses of normal and abnormal cellular systems to plasma radiation, which are useful for the development of advanced plasma therapy for cancer treatment at a later stage.

16:45
LW3 5 APNTP Inactivation of MS2 Bacteriophage: Effect of operating parameters on virucidal activity NID'A AL-SHRAIEDEH, MAHMOUD ALKAWAREEK, SEAN GORMAN, *School of Pharmacy, Queen's University Belfast, Belfast, BT9 7BL, UK* WILLIAM GRAHAM, *Centre for Plasma Physics, Queen's University Belfast, Belfast, BT7* BRENDAN GILMORE, *School of Pharmacy, Queen's University Belfast, Belfast, BT9 7BL, UK* Atmospheric pressure non-thermal plasmas (APNTP) provide a promising alternative method for surface decontamination. Norovirus is globally the most common etiological agent of acute non-bacterial gastroenteritis outbreaks. APNTP have proven to be effective in inactivation of MS2 bacteriophages, widely employed as surrogate for human norovirus. Here we explore the optimization of a helium-based kHz APNTP by varying the oxygen concentration (from 0 to 0.75%) in the feed gas and the operating frequency

(from 10 to 40 kHz). It has been established that both these changes increase the reactive oxide concentration in the plume and we see a correlation between both increasing oxygen concentration and operating frequency and reduction in survival density of treated bacteriophages. For example increasing the O_2 concentration from 0 to 0.5 to 0.75% increased the log reduction from 4.98 to 5.93 to 7.06, respectively. These results will be discussed in the context of recent studies where singlet delta oxygen was shown to cause MS2 phage inactivation.[*,†]

[*]Q T Algwari, PhD Thesis QUB (2011).
[†]E M Hotze *et al.*, *Environ. Sci. Technol.* 43(17): 6639-6645.

17:00
LW3 6 Influence of Uniform and Non-Uniform Regimes of Nanosecond-Pulsed Dielectric Barrier Discharges on Intracellular Biochemical Processes in 10T1/2 Cells ABRAHAM LIN, NATALIE SHAINSKY, DAYNNA PARK, THERESA FREEMAN, DANIL DOBRYNIN, ALEXANDER FRIDMAN, VANDANA MILLER, GREGORY FRIDMAN, *Drexel University* JEFFERSON UNIVERSITY COLLABORATION Before investigating plasma effects on differentiation, plasma regime limiting cell death must first be determined. We report the effects of dose on cell viability and compare with dose rates. Results allow for the safe operation of plasma in a regime where nanosecond pulsed DBD on mesenchymal stem cells (MSCs) promote differentiation with limited cell death. After optimizing plasma parameters, discharge energy and uniformity effects on differentiation in MSCs can be studied. We also report the effects of direct and indirect treatment on cellular behavior. C3H-10T1/2 MSCs were treated in 12 well plates and stained with two fluorescent markers: MitoSOX Red, which detects O2- and propidium iodide, which is a

live/dead stain. Dose vs dose rate effects were investigated, and direct vs indirect treatments were performed with nano-pulses at varying doses while keeping power and electric field the same. We show dependence of cell death with dose and not dose rate. Additionally, we demonstrated that direct treatment elicits greater ROS generation compared to that of indirect. A correlation of cell death and ROS generation with treatment dose is required to find optimal operating parameters for nano-plasma treatment of stem cells.

17:15
LW3 7 Growth control of budding yeast cells by oxygen-radical treatment TAKAYUKI OHTA, HIROSHI HASHIZUME, MASAFUMI ITO, *Meijo University* KEIGO TAKEDA, MASARU HORI, *Nagoya University* Microorganisms respond to stimuli or stresses such as chemicals, nutrition, pressure, heat and so on. Those stimuli lead to cell activation, inactivation or cell death, such as apoptosis and necrosis. Reactive oxygen species possibly affect cell growth as well as inactivation depending on stimuli. In this study, we investigated effects of oxygen-radical treatment on not only inactivation but also promoted/repressed cell growth of budding yeast by varying dose of atomic oxygen produced from an atmospheric-pressure oxygen radical source. Dose of atomic oxygen was estimated based on treatment time and oxygen flux. Cell growth was promoted with atomic oxygen between 0 and 2.1×10^{19} cm^{-2} dose of atomic oxygen. The treated cells were grown about 10 percent more proliferously than the control cells. Moreover, 64 percent of the treated cells to the control ones were inactivated at more than 4.2×10^{20} cm^{-2}. These results, therefore, suggested that atomic-oxygen dose had a potential to control mitotic promotion and repression, and inactivation of yeast cell growth.

SESSION LW5: HEAVY-PARTICLE COLLISIONS
Wednesday Afternoon, 2 October 2013; Room: Village Square at 15:30; Tom Kirchner, York University, presiding

Invited Papers

15:30
LW5 1 Heavy particle collisions in astrophysical, fusion, and other plasmas
DAVID SCHULTZ, *Department of Physics, University of North Texas*

Contemporary computational methods to treat few-body, atomic-scale interactions have opened opportunities to study them at a new level of detail to both uncover unexpected phenomena and to create data of unprecedented accuracy and scope for applications. Such interactions within gaseous, plasma, and even material environments are fundamental to such diverse phenomena as low temperature plasma processing of semiconductors, collapsing giant molecular clouds forming stars, fluorescent lighting, radiation treatment of disease, and the chemistry of earth's atmosphere. I will illustrate progress using examples from recent work treating heavy particle collision systems, for which our knowledge has been both subtly refined and significantly changed. Examples will include elastic and transport-related processes in fusion and solar-system plasmas, charge transfer leading to diagnostic light emission in planetary atmospheres and fusion plasmas, and excitation and ionization processes needed for plasma modeling and diagnostics.

Contributed Papers

16:00
LW5 2 Student Award Finalist - Interference in Recoil-Ion Momentum Spectra for ionization in p + H_2 Collisions SACHIN SHARMA, THUSITHA ARTHANAYAKA, AHMAD HASAN, BASU LAMICHHANE, JUAN REMOLINA, ALYSON SMITH, MICHAEL SCHULZ, *Missouri S & T - Rolla* We have performed a kinematically complete experiment on ionization in 75 keV p + H_2 collisions. The double differential cross sections (DDCS)

for fixed projectile energy loss as a function of the recoil momentum reveal interference due to indistinguishable diffraction of the projectile from the two atomic centers in the molecule. Earlier, we observed such structures in the projectile scattering angle dependent DDCS. In the present data the oscillations are more pronounced because the phase factor depends only on the recoil momentum, but not on the electron or projectile momentum. Recently, we found that interference structures are not present for an incoherent beam. However, it is not easy to unambiguously distinguish the coherence properties from projectile resolution effects,

which both depend on the beam profile. Since the recoil momentum resolution is independent of the beam profile, the present measurement is not affected by this problem. While the experiment has not been completed yet for an incoherent beam, we anticipate that we will be able to present such data by the time of the meeting.

16:15

LW5 3 Manipulating state-selective charge exchange in laser-assisted collisions of He^{2+} with atomic H* F. JAVIER DOMÍNGUEZ-GUTIÉRREZ, R. CABRERA-TRUJILLO, *Instituto de Ciencias Físicas - Universidad Nacional Autonoma de México* We solve the time-dependent Schrödinger equation within a finite-differences approach and the propagation Crank-Nicolson method to calculate the $n = 2, 3$, and total electron capture cross section of He^{2+} colliding with atomic H in the energy collision range 0.25-35 keV/amu. We use a laser pulse of 3, 2, and 1 fs at FHWM, wavelength of 800 nm and intensity 3.15×10^{12} W/cm^2. We demonstrate that the laser assistance in the collision increases an order of magnitude the electron charge capture in the 0.25-2 keV/amu energy collision range. We compare our numerical results with those obtained experimentally for the laser-free case to asses the validity of our method. Also, we study the effect of the laser pulse in the excitation cross-section for $n = 2$ states of the hydrogen atom and the dependence of the charge exchange as function of the FWHM of the laser pulse.

Invited Papers

16:30

LW5 4 Antiproton-Impact Single and Double Ionization of He and H$_2$* MICHAEL S. PINDZOLA, *Department of Physics, Auburn University*

A time-dependent close-coupling (TDCC) method has been used to calculate total cross sections for the antiproton-impact single and double ionization of He and H$_2$ for incident energies up to 100 keV. One active electron TDCC-3D calculations for the single ionization of He and H$_2$ yield cross sections at low energies higher than CERN experiments. On the other hand, two active electron TDCC-6D calculations for the single ionization of He and H$_2$ yield cross sections at low energies in reasonable agreement with CERN experiments. The TDCC-6D calculations also yield double ionization cross sections for He and H$_2$. Work is in progress on the calculation of fully differential cross sections for antiproton-impact ionization of a variety of atoms and diatomic molecules.

Contributed Papers

17:00

LW5 5 Time-dependent convergent close-coupling approach to antiproton-impact ionization of molecular hydrogen* A.S. KADYROV, I.B. ABDURAKHMANOV, D.V. FURSA, I. BRAY, *Curtin University* A time-dependent convergent close-coupling approach to the calculation of $\bar{p}$-H$_2$ collisions has been developed and applied to study single ionization. All possible orientations of the molecular target have been accounted for using an analytic orientation-averaging technique. Results for the total single ionisation cross section are compared with experimental data over the energy range of 1 keV to 2 MeV and good agreement is found. The approach provides the first theoretical confirmation of the experimentally observed phenomenon [H. Knudsen *et al.*, Phys. Rev. Lett. 105, 213201 (2010)] of target structure-induced suppression of the ionization cross section for low-energy antiproton-molecular hydrogen collisions.

17:15
LW5 6 ABSTRACT WITHDRAWN

SESSION MR1: POSTER SESSION III (8:00-9:30AM)
Thursday Morning, 3 October 2013
Exhibit Ballroom Foyer at 8:00

MR1 1 PLASMA-SURFACE INTERACTIONS

MR1 2 An experimental study of secondary electron emission in the limit of low electron energy* V.I. DEMIDOV, *WVU, Morgantown, WV; SPbGU, St. Petersburg, Russia* I.D. KAGANOVICH, *PPPL, Princeton, NJ* M.E. KOEPKE, *WVU, Morgantown, WV* Study of secondary electron emission (SEE) from solid surfaces is important for many areas of science and technology, including but not limited to the formation of electron clouds in particle accelerators, plasma measurements by electrostatic probes and operation of Hall plasma thrusters [1]. The measurements at low incident electron energy below 2eV are very challenging. The goal of this work is to measure SEE coefficient for molybdenum surface in contact with plasmas. In this study nearly mono-energetic electrons arising in plasma-chemical reactions like pair collisions of metastable atoms have been used for the measurements. Variation of the target voltage and measurement of the corresponding electron current from the mono-energetic electrons allows us to obtain the SEE coefficient. It is experimentally demonstrated that the coefficient is close to zero (less than 0.1) for clean targets and may have much higher value for contaminated targets with some absorbed gas on the surface.

[1]J. Cazaux. J. Appl. Phys. 111 (2012) 064903.

MR1 3 Energy dissipation in plasma treated Nb and Secondary Electron Emission for modeling of multipactor discharges* ANA SAMOLOV, SVETOZAR POPOVIC, LEPOSAVA VUSKOVIC, *CAS, Department of Physics, ODU, Norfolk, VA* MILOS BASOVIC, *CAS, Department of Mechanical Engineering, ODU, Norfolk, VA* FILIP CUCKOV, *College of Science and Mathematics, UMass Boston, Boston, MA* YEVGENY RAITSES, IGOR KAGANOVICH, *PPPL, Princeton, NJ* Electron-induced Secondary Electron Emission (SEE) is important in many gas discharge applications such as Hall thrusters, surface and multipactor discharges. Often they present the inhibiting phenomena in designing and operating of these systems, examples being the Superconducting Radio Frequency (SRF) accelerator cavities. The multipactor discharges depend on the resonant field configuration and on the SEE from the cavity surface. SEE is proportional to the energy dissipated by the primary electrons near the surface. Our analysis of energy spectra of secondary electrons indicates that the fraction of dissipated energy of primary electrons in solid reaches the maximum at the primary energies that produce the maximum yield. The better understanding of this mechanism is crucial for successful modeling of the multipactor discharge and design of vacuum electronic devices. We have developed an experimental set up to measure energy distribution of SEE from Nb coupons under different incident angles, since Nb is used for manufacturing of SRF accelerating cavities. Samples are placed in carousel target manifolds which are manipulated by robotic arm providing multiple degrees of freedom of a whole target system.

MR1 4 Characterization of a Helicon Plasma Source for Plasma Material Interactions PETER FIFLIS, DAVIDE CURRELI, KYLE LINDQUIST, DAVID RUZIC, *University of Illinois at Urbana Champaign* A helicon plasma device has been constructed at the Center for Plasma Material Interactions at the University of Illinois Experiments for the purpose of plasma material interaction studies. A MORI 200 helicon source is used to generate the plasma at 13.56 MHz. Measurements of the DC magnetic field provided by a Helmholtz coil were performed and are presented here as well as Langmuir probe measurements of the density and temperature. Radial and axial scans are performed to generate a profile of the plasma. A moveable stage for material substrates coupled with the experimental suite of material characterization devices at the Material Research Lab at the University of Illinois as well as this full characterization of the device will enable higher fidelity plasma material interaction studies, and potentially allow investigation of such phenomena as tungsten fuzz production.

MR1 5 FALCON Ion Source Focusing System Optimization for Effective Beam Impurities Mass-Separation OLEKSII GIRKA, STANISLAV HERASHCHENKO, IVAN BIZYUKOV, ALEKSANDER BIZYUKOV, KONSTANTIN SEREDA, *V.N. Karazin Kharkiv National University* The numerical and experimental investigation of the intrinsic capability for impurities mass-separation of FALCON ion source [1-2] was carried out. Optimal distance between the ballistic focusing cathodes and the magnetic lens was obtained via numerical calculations to provide maximum ion flux impurities separation. New magnetic lens for FALCON ion source was designed and manufactured as a result of calculations. A set of experiments on high-flux ion beam impurities mass-separation was carried out. Cyclohexane was used as a working gas. Cyclohexane molecule dissociated at gas discharge. As a result, there were hydrogen H^+ ions and C_XH_Y group ions. Polished SS304 samples coated with TiN were irradiated. Irradiation experiments showed that impurities are mass-separated and form the circle of a radius from 0.6 to 1.3 cm. There is free of impurities hydrogen only ion beam into this circle. Optimized FALCON ion source with closed drift provides particle and heat fluxes per unit surface of the target which are by the order of magnitude higher in comparison with existing ion sources designed for the plasma-surface interaction study.

[1]O. Girka, I. Bizyukov, K. Sereda, A. Bizyukov, M. Gutkin, V. Sleptsov, Rev. Sci. Instr., 83 (2012) 083501.
[2]M. Gutkin, A. Bizyukov, V. Sleptsov, I. Bizyukov, and K. Sereda, U.S. Patent US 7622721 B2 (2009).

MR1 6 Using Low Temperature Plasma as a Method of Decontamination of Fruits SOHEILA MOHADES, RICHARD JONAS, NAZIR BAREKZI, MOUNIR LAROUSSI, *Old Dominion University* Non-thermal atmospheric pressure plasmas have been investigated in biomedical applications as well as surface decontamination [1]. The characteristics of the helium plasma generated by the plasma pencil have been elucidated using spectroscopy methods, which revealed the formation of radical and metastable states [2]. The plasma pencil generates biologically tolerant plasma (BTP) that is not thermally harmful to biological living tissues. In addition, there are no persistent chemical residues as compared to the use of cleaning solutions. The rational for this study is that the low

thermal load and the reactive species can be exploited in decontaminating fruit surfaces. The BTP is evaluated in the killing of bacteria in solution and on the surface of food. The focus of this paper is to evaluate the efficacy of decontaminating surfaces of plants such as green peppers. The doses of plasma, media and growth conditions, as well as the general effect of plasma on fruit without bacteria are investigated using bacterial killing assays and spectroscopy.

[1]Laroussi M, Tendero C, Lu X, Alla S, and Hynes W L, 2006, *Plasma Processes and Polymers.* 3(6-7): p. 470–473.
[2]Jarrige J, Laroussi M, and Karakas E, 2010, *Plasma Sources Science and Technology.* 19(6): p. 1–11.

MR1 7 Experimental and computational study of plasma bullet reignition behind a thin dielectric slab PIETRO RANIERI, NATALIA BABAEVA, JOHN FOSTER, *University of Michigan* Ionization waves (IWs) propagating through plasma jets and helium channels are often observed as luminous fronts of the IWs and conventionally termed as plasma bullets. The preliminary experiments show that if a thin dielectric slab is placed in the helium channel as an obstacle for the bullet propagation, the discharge may reignite below the slab. This process is perceived as though the bullets propagate through the obstacle. The goal of this work is to find conditions under which the bullet can reignite behind the dielectric. The experimental setup consists of a corona discharge, with a single metal electrode, within a quartz tube. We study the influence of the dielectric constant, thickness and the length of the mica slab on the plasma jet behavior. We show that after the impact on the mica surface, the bullet partially reflects from the surface and plasma spreads along the surface. Depending on the location of the mica relative to the tube exit, its capacitance and opacity to photoionizing radiation, a second bullet can emerge below the slab. The computational model used in this work, *nonPDPSIM*, is a plasma hydrodynamics model in which continuity, momentum and energy equations are solved for charged and neutral species with solution of Poisson's equation for the electric potential.

MR1 8 Plasma surface kinetics studies of silicon dioxide etch process in inductively coupled fluorocarbon plasmas WONSEOK CHANG, *National Fusion Research Institute* DONG-HUN YU, *Kyung Won Tech.Inc* DEOG-GYUN CHO, YEONG-GEUN YOOK, POO-REUM CHUN, SE-AH LEE, *Chonbuk National University* DEUK-CHUL KWON, *National Fusion Research Institute* YEON-HO IM, *Chonbuk National University* With continuous decrease of nanoscale design rule, plasma etching processes to form high aspect ratio contact hole still remains a challenge to overcome their inherent drawbacks such as bowing and twisted feature. Due to their complexities there still exist big gaps between current research status and predictable modeling of this process. To address this issue, we proposed a surface kinetic model of silicon nitride etch process under inductively coupled fluorocarbon plasmas. For this work, the cut-off probe and quadrapole mass spectroscopy were used for measuring electrical plasma properties, the ion and neutral radical species. Furthermore, the systematic surface analysis was performed to investigate the thickness and chemical bonding of polymer passivation layer during the etch process. The proposed semi-global surface kinetic model can consider deposition of polymer passivation layer and silicon nitride etching self-consistently. The predicted modeling results showed good agreement with experimental data. We believe that our research will provide valuable information to avoid the empirical development of plasma etching process.

MR1 9 Injection of micron size droplets into vacuum* CAROLINE LIU, JOHN POULOSE, *The University of Texas at Dallas*

DAISUKE OGAWA, *Chubu University* MATTHEW GOECKNER, LAWRENCE OVERZET, *The University of Texas at Dallas* Previous experiments using direct liquid injection into plasma for film deposition produced films that had unwanted voids. We believe that the uneven deposition of polymer film is due to injected liquids not completely evaporating into the plasma and landing on the surface of the substrate instead. To address this issue, we chose to improve upon the previous film deposition chamber setup by modifying the injector to decrease the injected liquid droplet sizes. The literature presents multiple theories on liquid breakup into air and resultant droplet sizes but to the best of our knowledge, there is not much research on droplet breakup dynamics or resultant droplet sizes when liquid is injected into low pressure (< 20 mTorr) or vacuum. The literature states that liquid breakup in vacuum is caused by surface tension only and that the resulting droplet sizes produced by this mechanism are linearly dependent upon the orifice size. In our poster, we will describe previous work done, experimental setup along with experimental data on droplet sizes produced by orifices of various sizes when liquid is injected into low pressure.

MR1 10 PLASMA MODELING AND SIMULATIONS II

MR1 11 Kinetic global modeling of the rotating ionization regions in HiPIMS* SARA GALLIAN, RALF PETER BRINKMANN, *Ruhr University Bochum* WILLIAM N.G. HITCHON, *University of Wisconsin-Madison* High Power Impulse Magnetron Sputtering often develops a characteristic slowly rotating high emissivity region. This highly ionized region -or spoke- shows a stationary behavior in the current plateau region and rotates with $\Omega \approx 80$ kHz.[†] It is argued that these spoke-like structures determine the overall plasma density, carry most of the discharge current and are responsible for anomalous cross field electron transport. It is therefore fundamental to understand their formation and relevance in order to characterize the system behavior. First we develop a phenomenological fluid model[‡] and we analytically solve for the electron and neutral densities in a rotating steady state situation. Then, we develop a global model specifically for the spoke region that solves for the electron energy distribution function self-consistently with the rate equations for Ar and Al species. The fluxes of neutrals resulting from the movement of the volume are obtained self consistently from the phenomenological fluid model. We evolve the system employing a relaxation method, until convergence.

MR1 12 Modeling of capacitively and inductively coupled plasma for molecular decontamination* DIANA MIHAILOVA, GERJAN HAGELAAR, PHILIPPE BELENGUER, *Université de Toulouse & CNRS* CHRISTOPHER LAURENT, JUSLAN LO, BRUNO CAILLIER, LAURENT THERESE, PHILIPPE GUILLOT, *Centre Universitaire J.F. Champollion, Albi* This project aims to study and to develop new technology bricks for next generation of molecular decontamination systems, including plasma solution, for various applications. The contamination control in the

processing stages is a major issue for the industrial performance as well as for the development of new technologies in the surface treatment area. The main task is to create uniform low temperature plasma inside a reactor containing the object to be treated. Different plasma sources are modeled with the aim of finding the most efficient one for surface decontamination: inductively coupled plasma, capacitively coupled plasma and combination of both. The model used for testing the various plasma sources is a time dependent two-dimensional multi-fluid model. The model is applied to a simplified cylindrically symmetric geometry in pure argon gas. The modeling results are validated by comparison with experimental results and observations based on optical and physical diagnostic tools. The influence of various parameters (power, pressure, flow) is studied and the corresponding results are presented, compared and discussed.

*This work has been performed in the frame of the collaborative program PAUD (Plasma Airborne molecular contamination Ultra Desorption) funded by the French agency OSEO and certified by French global competitive clusters Minalogic and Trimatec.

MR1 13 Fully-kinetic Particle-in-Cell Simulations of Gas Switches CARSTEN THOMA, DALE WELCH, DAVID ROSE, WILLIAM ZIMMERMAN, CRAIG MILLER, ROBERT CLARK, *Voss Scientific, LLC* We describe a fully-kinetic electromagnetic particle-in-cell Monte Carlo (PICMC) computational model for the modeling of breakdown phenomena in electrophilic gases such as SF_6 and air which has been implemented into the hybrid-PIC code LSP. We present the results of 2D and 3D gas closing switch simulations in which all species are treated kinetically. We demonstrate that this PICMC approach can be used to follow the entire evolution of the switch, from the initial avalanche and streamer formation up to the fully conducting phase. We utilize an 18-species chemistry model for air which is shown to agree with swarm parameters (breakdown threshold, drift velocity) obtained by experiment. Photon transport and photo-ionization are also included to permit the modeling of phenomena such as cathode-directed streamers. This computational model will be used to help design closing switches for pulsed-power systems.

MR1 14 Generation of super-thermal electrons by intense electron beam in a dc discharge D. SYDORENKO, *University of Alberta, Edmonton, Alberta, Canada* I.D. KAGANOVICH, A.V. KHRABROV, *Princeton Plasma Physics Laboratory, Princeton, NJ* P.L.G. VENTZEK, L. CHEN, *Tokyo Electron America, Austin, TX* Experimental measurements of electron energy distribution function in a rf dc discharge with 800 V dc voltage reveal the presence of a peak of super-thermal electrons with energy in the range of 40-400 eV [1]. The cathode in the experimental device could emit electrons thus producing an electron beam. We used a particle-in-cell code [2] to investigate acceleration of plasma electrons by an electron beam in a dc discharge with parameters close to those of Ref. [1]. The beam excites electron plasma waves via the two-stream instability. Simulations show that the two-stream instability is intermittent, with quiet and active periods. During the quiet periods, the beam propagates through the plasma with minimal perturbations. During the periods of activity of the two-stream instability, the beam interacts with the plasma most intensively at locations where the global frequency of instability matches the local electron plasma frequency. There may be two resonance areas with intense oscillations usually near the edges of the plasma. These intense localized plasma oscillations produce peaks in the velocity distribution function similar to the ones measured in the experiment.

[1]L. Xu *et al.*, Appl. Phys. Lett. **93**, 261502 (2008).
[2]D. Sydorenko *et al.*, Phys. Plasmas **13**, 014501 (2006).

MR1 15 Modeling of recovery mechanism of ozone zero phenomenaby adding small amount of nitrogen in atmospheric pressure oxygen dielectric barrier discharges HARUAKI AKASHI, TOMOKAZU YOSHINAGA, *National Defense Academy* Ozone zero phenomena [1-3] in an atmospheric pressure oxygen dielectric barrier discharges have been one of the major problems during a long time operation of ozone generators. But it is also known that the adding a small amount of nitrogen makes the recover from the ozone zero phenomena. To make clear the mechanism of recovery, authors have been simulated the discharges with using the results of Ref. 3. As a result, the recovery process can be seen and ozone density increased. It is found that the most important species would be nitrogen atoms. The reaction of nitrogen atoms and oxygen molecules makes oxygen atoms which is main precursor species of ozone. This generation of oxygen atoms is effective to increase ozone. The dependence of oxygen atom density (n_O) and nitrogen atom density (n_N) ratio was examined in this paper. In the condition of low n_N/n_O ratio case, generation of nitrogen oxide is low, and the quenching of ozone by the nitrogen oxide would be low. But in the high ratio condition, the quenching of ozone by nitrogen oxide would significant. This work was supported by KAKENHI(23560352).

[1]K. H. Voigt *et al.*: Proc. Am. Water Works. Assoc. Ann. Conf., pp. 885–900 (1994).
[2]M. Taguchi *et al.*, Plasma Process Polym., pp. 719–727 (2007).
[3]G. Takahashi and H. Akashi, IEEE Trans. Plasma Sci. 39, pp. 2234–2235 (2011).

MR1 16 Numerical studies of collisionless scattering of an electron beam propagating in background plasma* ERINC TOKLUOGLU, ALEXANDER KHRABROV, IGOR KAGANOVICH, *PPPL* Beam-plasma systems are an important area of study for their application in plasma sources used in plasma processing. However the streaming of beam particles against a stationary plasma excite the two-stream instability. In 1D systems the result of this interaction is axial electrostatic Langmuir waves. However in real systems oblique modes can be excited, resulting in transverse electric fields which lead to the collisionless scattering of beam particles. In this work, using PIC code LSP we study the interaction of a 30 eV e-beam with a background plasma using an electrostatic 2D model. By tracking the scalar potential, the beam density, the particle phase space and using Fourier transform techniques, we look for evidence of oblique modes with both parallel and perpendicular wave numbers, study their time evolution and the consequent transverse scattering of beam electrons.

*This work was supported in part by the the U.S. Department of Energy.

MR1 17 Plasma-chemical simulation of negative corona near the inception voltage* FRANCISCO PONTIGA, FRANCISCO J. DURAN-OLIVENCIA, ANTONIO CASTELLANOS, *University of Seville* The spatiotemporal development of Trichel pulses in oxygen between a spherical electrode and a grounded plane has been simulated using a fluid approximation that incorporates the plasma chemistry of the electrical discharge. Elementary plasma processes, such as ionization, electron attachment, electron detachment, recombination between ions and chemical reactions between

neutral species, are all included in a chemical model consisting of 55 reactions between 8 different species (electrons, O_2^+, O_2^-, O_3^-, O^-, O_2, O, O_3). Secondary emission at the cathode by the impact of positive ions and photons is also considered. The spatial distribution of species is computed in three dimensions (2D-axysimmetrical) by solving Poisson's equation for the electric field and the continuity equations for the species, with the inclusion of the chemical gain/loss rate due to the particle interaction. The results of the simulation reveal the interplay between the different negative ions during the development of every Trichel pulse, and the rate of production of atomic oxygen and ozone by the corona discharge.

MR1 18 Non-Equilibrium Reaction Kinetics of an Atmospheric Pressure Microwave-Driven Plasma Torch: a Global Model* GUY PARSEY, YAMAN GÜÇLÜ, JOHN VERBONCOEUR, ANDREW CHRISTLIEB, *Michigan State University* In the context of microwave-coupled plasmas, within atmospheric pressure nozzle geometries, we have developed a kinetic global model (KGM) framework designed for quick exploration of parameter space. Our final goal is understanding key reaction pathways within non-equilibrium plasma assisted combustion (PAC). In combination with a Boltzmann equation solver, kinetic plasma and gas-phase chemistry are solved with iterative feedback to match observed bulk conditions from experiments; using a parameterized non-equilibrium electron energy distribution function (EEDF) to define electron-impact processes. The KGM is first applied to argon and "air" systems as a means of assessing the soundness of made assumptions. The test with "air" greatly increases the complexity by incorporating a plethora of excited states (e.g. translational and vibrational excitations) and providing new reaction pathways. The KGM is then applied to plasma driven combustion mechanisms (e.g. H2 or CH4 with an oxidizer source) which drastically increases the range of reaction time-scales. As the reaction mechanisms become more complex, availability of data will begin to hinder model physicality, requiring analytical and/or empirical treatment of gaps in data to maintain completeness of the reaction mechanisms.

MR1 19 Silicon oxide surface reaction modeling coupled with global bulk plasma model in inductive coupled fluorocarbon plasmas SE-AH LEE, POO-REUM CHUN, YEONG-GEUN YOOK, KWANG-SUNG CHOI, DEOG-GYUN CHO, *Chonbuk National University* DONG-HUN YU, *Kyung Won Tech.Inc* WON-SEOK CHANG, DEUK-CHUL KWON, *National Fusion Research Institute* YEON-HO IM, *Chonbuk National University* Ultra-high deep contact-hole etching is one of the critical issues in fabrication processes of the nanoscale devices. The fluorocarbon plasmas have been used to obtain the ideal etch profiles. As an effort to address this issue, we developed a predictable global plasma model that is coupled strongly with surface reaction and bulk plasma chemistry under fluorocarbon plasmas. For this work, bulk plasma diagnostics in inductively coupled fluorocarbon plasma was performed by quadruple mass spectrometry, Langmuir probe, and cut-off probe. Based on bulk plasma diagnostic data and SiO_2 etch rates, key information such as rate coefficient and reaction paths for realistic bulk plasma and surface chemistry could be obtained in this work. Furthermore, global plasma model was strongly coupled with surface reaction model to capture the realistic plasma phenomena. Finally, the predicted modeling results of etch rate as functions of plasma conditions showed good agreement with experimental data of SiO_2 etching. We believe that this model approach can provide useful and effective route to predict the complex plasma phenomena for oxide etching process in fluorocarbon plasma.

MR1 20 GPU based 3D feature profile simulation of high-aspect ratio contact hole etch process under fluorocarbon plasmas POO-REUM CHUN, SE-AH LEE, YEONG-GEUN YOOK, KWANG-SUNG CHOI, DEOG-GEUN CHO, *Chonbuk National University* DONG-HUN YU, *Kyung Won Tech.Inc* WON-SEOK CHANG, DEUK-CHUL KWON, *National Fusion Research Institute* YEON-HO IM, *Chonbuk National University* Although plasma etch profile simulation has been attracted much interest for developing reliable plasma etching, there still exist big gaps between current research status and predictable modeling due to the inherent complexity of plasma process. As an effort to address this issue, we present 3D feature profile simulation coupled with well-defined plasma-surface kinetic model for silicon dioxide etching process under fluorocarbon plasmas. To capture the realistic plasma surface reaction behaviors, a polymer layer based surface kinetic model was proposed to consider the simultaneous polymer deposition and oxide etching. Finally, the realistic plasma surface model was used for calculation of speed function for 3D topology simulation, which consists of multiple level set based moving algorithm, and ballistic transport module. In addition, the time consumable computations in the ballistic transport calculation were improved drastically by GPU based numerical computation, leading to the real time computation. Finally, we demonstrated that the surface kinetic model could be coupled successfully for 3D etch profile simulations in high-aspect ratio contact hole plasma etching.

MR1 21 Plasma Sheath Properties at Gas-Dielectric Interface ASHRAF FARAHAT, *King Fahd University of Petroleum & Minerals* Microdischarges have numerous properties that have been investigated in a number of applications including microdischargers for small spacecraft and plasma displays. A two dimensional flowing gas-plasma model is developed to investigate microdischarges properties near dielectric surfaces. The model consists of electrons, ions and metastable species conservation equations and the Poisson equation and is applied to a 1.2 mm length, 0.2 mm height argon filled microdischarger including anodes and a cathode separated by a dielectric material. Initial electron swarm is assumed to be uniform in the volume and equal to 10^8 m^{-3}. Secondary emission due to ions and excited particles impact is considered with a coefficient equal to 0.05. We present early nanoseconds charge development near the dielectric surface and at the electrodes – dielectric boundaries. Two-dimensional plots of the charged and excited-species densities are presented and discussed. Electrons' temperature reaches 11.7 eV after 580 ns. Positive dielectric surface charges results in an anode virtual expansion which help in the formation of an ion sheath that gradually decreases the potential gradient between electrodes.

MR1 22 Investigation of Isentropic Coefficient in Non-LTE Hydrogen Thermal Plasma ROHIT SHARMA, *Satyam Institute of Engineering & Technology, Amritsar, Punjab, India-143507* KULDIP SINGH, *Guru Nanak Dev University Amritsar, Amritsar, Punjab, India-143005* The isentropic coefficient in non-LTE hydrogen plasma has been examined in the temperature range from

6000K to 60000K at pressures of 1, 10 and 100 atm for different values of non-equilibrium parameters θ by taking into account the influence of electronically excited states. The two cases of hydrogen thermal plasma have been considered (i) the ground state (GS), in which all the plasma species are assumed to be in the ground state and (ii) the excited state (ES), in which all the species are distributed in the various possible excited states. It has been observed that isentropic coefficient for hydrogen thermal plasma remains almost constant at 1.16 when degree of ionization varies from 0.1 to 0.8 with some dependence on the non-equilibrium parameter θ. Further, it is inferred that electronically excited states play a significant role at high pressure in affecting the isentropic coefficient of hydrogen thermal plasma.

MR1 23 INDUCTIVELY COUPLED PLASMAS

MR1 24 Effect of Radio Frequency Bias on the Plasma Density and Electron Heating in Inductive Discharge HYO-CHANG LEE, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University, Seoul 133-791, Korea* We show experimental observations of the radio frequency (RF) bias effect on the plasma density and electron heating in RF biased inductively coupled plasma (ICP). When the ICP power is relatively small or the discharge is in capacitive mode, the plasma density increases considerably with the bias power, while decrease in the plasma density is observed when the discharge is in inductive mode. The change of the plasma density can be explained by the balance between total power absorption and power dissipation. With small RF bias powers in the ICP, the electron energy distribution (EED) evolves from bi-Maxwellian distribution to Maxwellian distribution by enhanced plasma bulk heating. In the capacitive RF bias dominant regime, however, high energy electrons by the RF bias are heated on the EEDs in the presence of the ICP. The collisionless heating mechanism of the high energy electrons transits from collisionless inductive heating to capacitive coupled collisionless heating by the electron bounce resonance in the RF biased ICP.

MR1 25 Inductive and Capacitive Power Deposition of Antiparallel Current Source using Plasma Modeling KALLOL BERA, JOHN FORSTER, SHAHID RAUF, UMESH KELKAR, *Applied Materials, Inc.* Inductive and capacitive power deposition to plasma for anti-parallel current carrying conductors as plasma source has been investigated at different frequency and pressure using plasma modeling. In our model capacitive electric field is calculated by solving scalar potential, φ, in Poisson equation. In addition, induced magnetic and electric fields have been solved based on coil current. The power deposition to electrons includes both inductive and capacitive power deposition. The coupled set of equations governing the scalar potential, φ, momentum equation for ions and drift-diffusion equations for electrons are solved implicitly in time. The characteristic discharge dimension we considered is a few cm. The rf current and voltage are applied to the rod. At intermediate pressure of a few Torr at 13.5 MHz, it is found that ICP-only operation requires very high current. In this condition the skin depth being large the inductive coupling is not effective. With increase in frequency to 60 MHz, the skin depth decreases, the inductive coupling improves and current requirement decreases. At lower pressure the current requirement decreases as the inductive coupling improves due to smaller skin depth. The inductive and capacitive power couplings to the plasma at different operating frequency and pressure have been characterized for the plasma source.

MR1 26 E to H Heating Mode Transition and Hysteresis in Inductively Coupled Plasma HYO-CHANG LEE, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University, Seoul 133-791, Korea* Inductively coupled plasma has been known to have two distinct modes, capacitive mode (E mode) and inductive mode (H mode), and the dramatic changes in the plasma parameters and the hysteresis has been observed on the E to H and H to E heating mode transitions. In this work, we investigate two main points: 1) origin of the hysteresis by considering impedance matching circuit, 2) smooth transition of the plasma density through a comparison between argon and helium. From our experimental effort, it is found that the E to H heating mode transition and the hysteresis are caused by both the system power loss and the nonlinear behaviors of the plasma.

MR1 27 Evolution of Electron Temperature and Coupling between Electron Temperature and Power Absorption HYO-CHANG LEE, SEUNGJU OH, YOUNG-CHEOL KIM, CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University, Seoul 133-791, Korea* Power absorption to plasma is a fundamental and core issue in the field of ionized gases and plasma physics, and it is generally known that in the thermal equilibrium plasma with Maxwellian electron distribution, the power absorption in global model is decoupled to electron temperature (T_e). However, we show experimentally and theoretically that T_e is quite coupled to the power absorption. With increase in the power absorption to the plasma, the power absorption and the T_e are abnormally evolved due to a competition between the step-ionizations and the gas heating.

MR1 28 A study of increasing radical density and etch rate using remote plasma generator system JAEWON LEE, KYUNGHYUN KIM, SUNG-WON CHO, CHIN-WOOK CHUNG, *Hanyang University* To improve radical density without changing electron temperature, remote plasma generator (RPG) is applied. Multistep dissociation of the polyatomic molecule was performed using RPG system. RPG is installed to inductively coupled type processing reactor; electrons, positive ions, radicals and polyatomic molecule generated in RPG and they diffused to processing reactor. The processing reactor dissociates the polyatomic molecules with inductively coupled power. The polyatomic molecules are dissociated by the processing reactor that is operated by inductively coupled power. Therefore, the multistep dissociation system generates more radicals than single-step system. The RPG was composed with two cylinder type inductively coupled plasma (ICP) using 400 kHz RF power and nitrogen gas. The processing reactor composed with two turn antenna with 13.56 MHz RF power. Plasma density, electron temperature and radical density were measured with electrical probe and optical methods.

MR1 29 Measurement of electron energy distribution functions in a low pressure and low density inductively coupled plasma HYUN-JU KANG, YU-SIN KIM, *Department of Electrical Engineering, Hanyang University* DONG-HWAN KIM, *Department of Nanoscale Semiconductor Engineering, Hanyang University* CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University* Electron energy distribution functions (EEDFs) and electron densities versus RF power were measured in a low-pressure argon discharge. The measurement was

performed with an RF compensated single Langmuir probe, accurate measurement circuits and improved data acquisition algorithms in order to obtain the high quality EEDFs. As power increases, the EEDF evolves from a bi-Maxwellian distribution to a Maxwellian distribution. In low density region, a bi-Maxwellian distribution is clearly observed and their density is higher than the estimated density with a Maxwellian distribution. Energetic electrons and their high temperature that are directly related to collisional energy loss for creating one electron–ion pair can explain these results.

MR1 30 MICRODISCHARGES: DC, RF, MICROWAVE

MR1 31 Study of the maximum length of atmospheric pressure microplasma jets ANNE BOURDON, FRANCOIS PECHEREAU, JAROSLAV JANSKY, *laboratory EM2C, Ecole Centrale Paris, France* Since a few years, atmospheric pressure microplasma jets formed by pulsed helium discharges ignited in thin dielectric tubes have received considerable interest due to their potential for biomedical applications. At the tube exit, in most experimental set-ups, the maximum length of the microplasma jet is related to the helium-air mixing. Indeed, the discharge front is usually tubular at the tube exit and its radius decreases during its propagation, as the discharge is constrained to propagate in the region with a sufficient helium concentration. However, when a voltage pulse with a short decrease time is used in experiments, the maximum length is related to the voltage decrease with a decrease of the emission of the discharge front. As the discharge front stops propagating, an increase of emission is observed in the tube. In this work, we propose to simulate in 2D the discharge dynamics and to study the influence of the voltage decrease time on the maximum length and discharge structure of a microplasma jet. Results will be compared with experiments. Finally, we propose to simulate in 2D the interaction of two counter propagating microplasma jets to study the influence of the polarity of discharges and of the dielectric tube radius on the length of both plasma jets.

MR1 32 Measurement of electric fields in a helium micro-hollow cathode discharge by forbidden transitions SHINICHI NAMBA, DAISUKE MAKI, KEN TAKIYAMA, *Graduate School of Engineering, Hiroshima University* Micro-hollow cathode discharges operated at high pressure has been attracting a great deal of interest for various application, such as, excimer light sources, medical/biological fields and microchemical reactor. In the plasmas, the electric (E) field in the sheath region plays an important role to generate and sustain the plasmas. In order to determine the E field in the He microplasma, the emissions of allowed (He I 2P-4D: 492.19 nm) and forbidden (2P-4F: 492.06 nm) lines were observed. The cathode and anode were both made of brass, and ceramic disks were used to electrically insulate the electrodes. The cathode disk had inner hole diameter of 1.0 mm (length: 2.0 mm). The gas with a flow rate was 1.0 L/min. The discharge was operated at voltages of 250 V, currents of 8 mA and gas pressures up to 100 kPa. The plasmas in the cathode opening were observed using a visible spectrometer. The forbidden line associated with the level mixing of upper levels was observed in the cathode surface, indicating that the high E field was formed. As the intensity ratio of forbidden to the allowed lines is a function of the E field which is calculated by perturbabation theory, we derived the field strength of 18 kV/cm at 1.0 mm cathode surface.

MR1 33 Electron dynamics in dual frequency operation of a helium-based radio frequency atmospheric discharge LAURA COX, COLM O'NEILL, ANDREW GIBSON, BILL GRAHAM, *Centre for Plasma Physics, Queen's University Belfast, UK* TIMO GANS, DEBORAH O'CONNELL, *York Plasma Institute, University of York, UK* The effects of dual frequency operation on the electron energies in a capacitively coupled radio frequency discharge of a plasma jet were studied. The device consists of two stainless steel electrodes of area 1×30 mm, spaced 1 mm apart. The gap spacing is bounded on each side by quartz glass windows. A gas mixture of 1 slm helium, 5 sccm oxygen and 1 sccm argon is flowed through. The top electrode was operated at a frequency of 13.33 MHz and the lower at 39.99 MHz, each with a voltage of approximately $200V_{p-p}$. The phase relationship between the two was varied in 30 degree steps. Phase and space resolved optical emission spectroscopy was used to observe the spatio-temporal behavior of higher energy electrons involved in excitation throughout one 75.02 ns RF period. Images were taken at 1 ns intervals. Optical filters at 706 nm and 750 nm were used to view emission from the He ($3s^3S - 2p^3P$) and Ar ($2p_1 - 1s_2$) transitions, corresponding to excitation energies above 22 eV and 13 eV respectively. The results show a change in excitation structures and relative intensity dependent on the phase relationship between the two frequencies. The results are compared with simulation results under these conditions, which allows further insight into the plasma behavior.

MR1 34 Comparison of kinetic, fluid and global modeling of rf discharges at amospheric pressure* TORBEN HEMKE, DENIS EREMIN, RALF PETER BRINKMANN, THOMAS MUSSENBROCK, *Ruhr-Universitaet Bochum* Modeling and simulation of microplasmas is an important key for understanding their physical properties. In particular, not all available plasma diagnostics are applicable to the small dimensions of microplasmas. Thus, theoretical approaches offer in many cases the only way to gain physical insight. The general modeling simulation techniques are kinetic, fluid and global models. In this order they decrease in computational effort, but also in physical accuracy. The computational costs have espessically to be taken into account when dealing with large sets of particle species and chemical reactions. In this contribution, we report on different implementations of the three different modeling approaches for (1d) rf driven micorplasmas at atmospheric pressure in a helium-nitrogen mixture. In conclusion, we show the benefits and limitations of each simulation technique.

MR1 35 Hollow radial electron density profiles in surface wave discharges. An inside job?* MANUEL JIMENEZ-DIAZ, SARA RAHIMI, EMILE A.D. CARBONE, JAN VAN DIJK, *Department of Applied Physics, Eindhoven University of Technology* In many microwave excited plasmas, there is a part of the discharge (tube) hidden from optical access e.g. because of the metal parts that cover it; it is the region where the transformation occurs between the EM modes found in the (metal) waveguide to modes in the plasma (waveguide). Because in most of cases optical access is not an option here, studies of this region remain scarce. Regardless of this, it is a well-known fact that the discharge tube can easily break due to the high temperatures inside the launcher of surfaguide discharges, which means the temperature is higher there than in other regions of the plasma. In this work, we use a 2D model to show how the inner region changes for increasing power absorbed and electromagnetic wave frequency. The shaping of the EM coupling into the plasma region by the cavity is explored as well. We discuss when the hollow radial profiles for the electron density appear in a surfaguide plasma, and how they are related to the radial inhomogeneity of

the EM fields and the plasma properties (e.g. gas temperature). All these results were obtained using the modeling platform Plasimo.

MR1 36 Self-Organized Patterns of Spots In DC Glow Microdischarges in Krypton* WEIDONG ZHU, *Department of Applied Science and Technology, Saint Peter's University, 2641 Kennedy Blvd, Jersey City, NJ 07306, USA* PEDRO G.C. ALMEIDA, MIKHAIL S. BENILOV, DIEGO F. SANTOS, *Departamento de Física, Universidade da Madeira, Largo do Município, 9000 Funchal, Portugal* PRAJWAL NIRAULA, *Department of Applied Science and Technology, Saint Peter's University, 2641 Kennedy Blvd, Jersey City, NJ 07306, USA* Self-organized patterns of cathodic spots have been observed in DC microdischarges in xenon. Modeling of microdischarges in xenon has revealed existence of multiple solutions. Some of the solutions describe normal discharges, others describe 2D patterns of cathodic spots, and others describe 3D patterns similar to those observed in experiments. A very interesting question is why modes with self-organized patterns have been observed in DC microdischarges in xenon but not in other gases. Modeling suggests that self-organized patterns can be observed in gases other than xenon provided that conditions are right. In the present work, self-organized patterns of spots observed in DC microdischarges in krypton are reported. The experiments are guided by modeling and the discharge device employed in the experiments consists of a molybdenum foil as the anode, an aluminum oxide plate as the dielectric spacer and another molybdenum foil as the cathode. Each layer of the device is 0.25 mm thick. Circular openings of 0.75 mm in diameter are prepared on both anode and dielectric spacer and are aligned. The whole device is assembled by Torr Seal epoxy. Research grade krypton is used to fill the chamber to a pressure of 200-1200 Torr.

MR1 37 THERMAL PLASMAS, ARCS, JETS, SWITCHES, OTHERS

MR1 38 Simulation Research of Influence of Retarded Axial Magnetic Fields on Vacuum Arc in DC Interruption Process* LIJUN WANG, SHENLI JIA, LILAN HU, LING ZHANG, ZONGQIAN SHI, SHUWEI FAN, *Xi'an Jiaotong University* In this paper, based on magnetic-hydrodynamic dynamic (MHD) model, the influence of retarded axial magnetic fields (AMFs) on vacuum arc characteristics in fast direct current (DC) interruption process was simulated and analyzed. Magnetic field calculation results showed that the faster current decreased, the more obviously AMF lagged behind arc current. On one hand, higher AMF strength can restrain the contraction of vacuum arc more efficiently, so that the distribution of current density in arc column region was more homogeneous; on the other hand, higher AMF strength restrained plasma diffusion in current zero stage, which made residual plasma density between electrodes at current zero moment keep higher value, and the possibility of arc re-ignition increased as well. By weakening AMF strength at current dropping stage, DC arc can be more easily interrupted successfully. The correctness of simulation results also was verified by experimental results. In artificial

crossing-zero stage, as current decreased, the decrease of light intensity and arc diameters were consistent with those in experimental results.

MR1 39 Flow Dynamics from a Nonequilibrium Atmospheric-Pressure Arc Discharge Jet JUAN TRELLES, *University of Massachusetts Lowell* Plasma jets are used as directed sources of energy, momentum and excited species fluxes in diverse technologies, such as spray coating, chemical synthesis, waste treatment and pyrolysis. The fluid, thermal and electromagnetic dynamics from the jet produced by a direct-current non-transferred arc plasma torch are explored using time-dependent three-dimensional simulations encompassing the dynamics of the arc inside the torch, the development of the jet through the outside environment, and the later impingement of the jet over a substrate. The plasma flow is described mathematically by a chemical equilibrium and thermodynamic nonequilibrium (two-temperature) model and numerically by a coupled fluid-electromagnetic transport model and a Variational Multiscale Finite Element Method. Simulation results uncover various aspects of the flow dynamics, including the jet forcing due to the movement of the arc, the prevalence of deviations between heavy-species and electron temperatures in the plasma fringes, the development of shear flow instabilities around the jet, the occurrence of localized regions with high electric fields far from the arc, the fluctuating expansion of the gas ejected from the torch, and the formation and evolution of coherent flow structures.

MR1 40 PLASMA ETCHING

MR1 41 Reduction of Aspect Ratio Dependency in Silicon Trench Etch* ROBERT BATES, *University of Texas at Dallas* The etch rate of deep features in silicon, such as trenches and vias, can vary significantly with the changing aspect ratio (AR) of the feature. This work focused on using a continuous plasma process utilizing a gas mixture of SF_6-C_4F_8-Ar to produce trenches of varying widths and depths. Optical and electrical diagnostics of percent flow, total flow and RF bias on trench profiles were investigated. Experiments were also performed to show that the etch rate of low AR features can be reduced through the deposition of a passivation layer and thereby allow larger AR features to "catch up". It is also possible to invert the ARDE in certain circumstances.

MR1 42 Plasma Processing of Large Curved Nb Surfaces with Application to SRF Cavities* JANARDAN UPADHYAY, DO IM, FREDERICK MILLER, SVETOZAR POPOVIC, LEPOSAVA VUSKOVIC, *Center for Accelerator Science, Department of Physics, ODU, Norfolk, VA* LARRY PHILLIPS, ANNE-MARIE VALENTE-FELLICIANO, *TJNAF, Newport News, VA* Surface modification of superconducting radio-frequency (SRF) cavities are a promising alternative to the wet etching technologies that are currently applied to Nb cavities. We have built a Nb etching cylindrical discharge chamber, comparable by volume to 1.5 GHz resonant cavity with 8 observation ports for holding the Nb samples, spectral observations, and electric probe measurements. Several asymmetric discharge configurations were tested with a variety of pressure,

power and gas composition combinations. All discharges have been operated in Ar/Cl$_2$ gas mixtures with Cl$_2$ content up to 15%. Plasma parameters were evaluated using a Langmuir probe, and an optical emission spectroscopy based on the relative intensities of two specific Ar 5p-4s lines at 419.83 and 420.07 nm, respectively. We have also carried out a systematic study of atomic and molecular spectra during Nb etching in order to determine the most appropriate process signature. The effects of discharge conditions and parameters are intended to be used as guidelines for optimal design of SRF cavity etching processes.

MR1 43 Development of Magnet-Free Sputtering System for Dielectric Film Deposition with Surface-Wave Excited Plasma* TOMONORI NODA, TOSHIYA HAGIHARA, HIROTAKA TOYODA, *Nagoya University* In various thin film deposition technologies such as plasma-enhanced chemical vapor deposition or vacuum evaporation, plasma sputtering is known as one of common technology because of its applicability to the deposition of high-melting-point materials on glass or polymer substrates. However, degradation of interface and/or and crystalline quality due to impingement of high-energy-particles is sometimes one of issues for sputter deposited films. In our previous study, we have shown that high energy negative ions are localized not at high plasma density regions but at low plasma density regions in the case of dielectric RF sputtering. This fact suggests that the movement of the magnet (and the plasma) that is common in industrial sputtering system results in non-uniform irradiation of high energy negative ions on the depositing film surface. To solve such problem, we propose uniform sputtering of dielectric materials without using magnets, i.e., using uniform surface-wave excited plasma and RF biasing. With use of a microwave-plasma coupling antenna that can sustain plasma at low pressures less than 1 Pa, uniform sputtering of dielectric materials will be demonstrated.

MR1 44 Dynamics of pulsed laser deposition plasmas KIM PEERENBOOM, JAN VAN DIJK, *Eindhoven University of Technology* RIK GROENEN, KASPER ORSEL, BERT BASTIAENS, *University of Twente* Pulsed laser deposition has proven to be a successful technique to deposit complex materials with atomic precision. In the first stage of the pulsed laser deposition process, target material is ablated by irradiation with a high power pulsed laser. This ablated material develops into a plasma plume which expands and is finally deposited on a substrate. Although the pulsed laser deposition technique itself is simple, the physical processes behind it are rather complex. As a result of this complexity, up to now understanding of the pulsed laser deposition process is limited to empirical knowledge. To establish the link between the experimental parameters (e.g. laser pulse duration, background pressure) and the deposited film, quantification of the species fluxes in the plasma plume is crucial. As a first step towards such a quantification, we will present a numerical simulation studying the influence of the background gas on the dynamics of the plasma plume.

MR1 45 Cluster incorporation during amplitude modulated VHF discharge silane plasmas* SUSUMU TOKO, YEON-WON KIM, YUJI HASHIMOTO, YOSHINORI KANEMITU, HYUNWOONG SEO, GIICHIRO UCHIDA, KUNIHIRO KAMATAKI, NAHO ITAGAKI, KAZUNORI KOGA, MASAHARU SHIRATANI, *Kyushu University* VHF discharge silane plasmas have been widely used to deposit hydrogenated amorphous silicon (a-Si:H) films. In this plasma process, while the higher VHF power brings about the higher deposition rate, it also results in generating a lot of Si clusters, which are mainly responsible for light degradation of a-Si:H thin films. Therefore, it is important to clarify a growing process and behavior of clusters and to develop a method for suppressing cluster incorporation into films. Here we investigated effects of amplitude modulated VHF discharge silane plasmas on cluster incorporation into Si thin films by in-situ measurements with quartz crystal microbalances (QCM). Experiments were carried out in a multi-hollow discharge plasma CVD reactor with QCM [1,2]. The amount of cluster incorporation in initial phase and steady state is found to be controlled by modulation level and frequency of the amplitude modulation.

[1] Y. Kim *et al.*, Jpn. J. App. Phys. **52** (2013) 01AD01.
[2] K. Koga *et al.*, J. Vac. Sci. Technol. **A22** (2004) 1536.

MR1 46 A study on the characteristics of Ti and C thin film prepared by Modulated Sputtering System (MSS) TAE-HWAN KIM, *Department of Electrical Engineering, Pusan National University* DAE CHUL KIM, YONGHYUN KIM, YOUNG-WOO KIM, *Plasma Technology Research Center, National Fusion Research Institute* HO JUN LEE, *Department of Electrical Engineering, Pusan National University* SEUNGHEE HAN, *Korea Institute of Science and Technology* In this work, newly designed bipolar pulsed DC power supply (Modulator) for MSS was developed to improve the properties of thin films. During the pulse on-time of the modulator driven by external TTL pulse, a negative voltage is applied to deposit the thin films on the substrate. Also, a positive voltage is applied while the pulse off-time of the modulator, and then ion beams are generated from the plasma and driven away to the substrate. Experiment was performed for various bias voltage, frequency and duty cycle. We also observed Ti thin films deposited by the MSS. The crystal structure, surface roughness, and thickness were investigated by using X-ray diffraction (XRD), atomic force microscopy (AFM), alpha step and scanning electron microscopy (SEM) measurement, respectively. The crystal orientation of the Ti films changes from a (002) preferred orientation to an entirely (100) orientation with increasing the ion beam energy. Also, we investigated bonding structure, sheet resistance, and thickness of carbon thin film by using micro-Raman spectroscopy, thin films resistor analyzer, and alpha step. In the case of the sheet resistance of carbon films, sheet resistance was decreased by increased ion beam energy. And then, it was increased again through continuously ion beam energy increasing more than 100 eV.

MR1 47 Thin Film Deposition of MAX Phase Nb-Al-C Compounds on Stainless Steel Substrates Using a Magnetized Sheet Plasma Source* JANELLA MAE SALAMANIA, HENRY RAMOS, *Plasma Physics Laboratory, National Institute of Physics, University of the Philippines - Diliman* Thin films of the Nb-Al-C system were deposited on stainless steel substrates through the magnetron sputtering mode of the Magnetized Sheet Plasma Facility from elemental source of Nb, Al metals and reactive gas CH$_4$. Niobium and aluminum targets were first sputtered using argon plasma and were deposited together with CH$_4$ gas onto the substrates. Various parameters such as target bias, time, filling pressure and extraction current were varied. Synthesized thin films were then characterized using X-ray diffraction (XRD),

Scanning Electron Microscopy (SEM), Energy Dispersive X-Ray Spectroscopy (EDX) and Raman Spectroscopy. XRD spectra of the samples show that MAX phases of the Nb-Al-C family are present on the films, specifically, the 413 phase (Nb_4AlC_3). EDX and Raman spectra confirm the presence of the elemental niobium, aluminum and carbon in the films. Raman spectra show that excess carbon formed fine graphite crystallites. SEM surface images show that the resulting films follow the contours of the SS substrate. The cross-sectional images show micron scale thickness deposited above the SS substrates.

MR1 48 Parameter manipulation in the Synthesis of Ti-Cd-C Films via Reactive Sputtering in a Magnetized Sheet Plasma Facility* MATTHEW BRYAN VILLANUEVA, HENRY RAMOS, *Plasma Physics Laboratory, National Institute of Physics, University of the Philippines-Diliman* Titanium-cadmium-carbon (Ti-Cd-C) deposits were achieved through reactive sputtering in a magnetized sheet plasma facility (MSPF). Titanium and cadmium metals (99.9% purity) were used as sputter targets, and high purity methane as the reactive gas. Parameters investigated were target bias, deposition duration, filling pressure, gas ratio, gas type such as acetylene, and magnetic configuration. Through X-ray diffractometry, peak signals at $2\theta = 23.3°$ for the treatment which implemented an independent sputtering step at -200 V target bias, and $2\theta = 12.34°$ for direct reactive sputtering only with -800 V target bias were recorded. Both XRD results are indicative of the formation of Ti_2CdC, a theorized solid solution of $M_{n+1}AX_n$ phase variety.

MR1 49 PLASMA DEPOSITION

MR1 50 Ar/N2 Magnetron Sputtering Discharges to Control Growth of Transparent Conducting Oxide Films KOICHIRO OSHIKAWA, IPING SUHARIADI, DAISUKE YAMASHITA, HYUNWOONG SEO, KUNIHIRO KAMATAKI, GIICHIRO UCHIDA, KAZUNORI KOGA, MASAHARU SHIRATANI, NAHO ITAGAKI, *Kyushu University* Here we demonstrate advantageous application of Ar/N2 discharges to magnetron sputtering deposition of ZnO films for crystal growth control [1]. Optical emission spectroscopy reveals that atomic nitrogen in Ar/N2 discharges plays important roles in determining the crystal grain density as well as the surface morphology of ZnO films. By utilizing 10-nm-thick ZnO films fabricated in Ar/N2 discharges as buffer layers, we have succeeded in fabricating low-resistive ZnO:Al (2wt.%) films, the properties of which are superior to those of conventional ZnO:Al films fabricated without N2. The resistivity of ZnO:Al films with buffer layers is a constant low value of 2.6×10^{-4} $\Omega \cdot cm$ in the thickness range 20-200 nm, whereas the resistivity of conventional ZnO:Al films increases from 6.3×10^{-4} to 1.5×10^{-3} $\Omega \cdot cm$ with decreasing the thickness from 200 nm to 20 nm. Effects of Ar/N2 discharges on other transparent conductive oxides including In2O3:Sn will be discussed at the conference.

[1]N. Itagaki *et al.*, Appl. Phys. Express **4** (2011) 011101.

MR1 51 Growth of Amorphous Silicon Nitride Films on Silicon Wafer by Atmospheric Pressure Plasma Jet* XUEQIANG ZHANG, *Radiation Laboratory & Department of Chemistry and Biochemistry, University of Notre Dame* SYLWIA PTASINSKA,

Radiation Laboratory & Department of Physics, University of Notre Dame Atmospheric pressure plasma jets (APPJ) possess favorable advantages including low temperature, low cost and the potential to be applied in areas such as coating and material functionalization. Silicon nitride is the most important non-oxide ceramics and multi-methods have been employed to grow silicon nitride, but its application has been limited by its high production cost. Here we demonstrate a method in which APPJ was used to grow amorphous silicon nitride films on a silicon wafer. Hydrofluoric acid pretreated Si wafers were treated by the helium APPJ at ambient air conditions. X-ray photoelectron spectroscopy (XPS) showed that silicon nitride species with binding energy at 398 eV are formed on the Si surface. XPS spectra taken from different areas of Si wafers indicate that the formation of nitrides is highly localized due to direct interactions with the plasma jet. This can also be verified by XPS 2-D mapping of N1s signal. Other gases such as N_2, N_2O, NO, NH_3 were doped into the helium stream and it was found that nitrogen and ammonia gas mixed with helium produced the highest intensity of a nitride signal. Optical emission spectra of APPJ were measured in order to understand the nitride formation mechanism.

MR1 52 BIOLOGICAL AND BIOMEDICAL APPLICATIONS OF PLASMAS

MR1 53 Reaction mechanism between cell membranes of P. digitatum spores and oxygen radicals MASAFUMI ITO, HIROSHI HASHIZUME, TAKAYUKI OHTA, *Faculty of Science and Technology, Meijo University* KEIGO TAKEDA, KENJI ISHIKAWA, MASARU HORI, *Graduate school of Engineering, Nagoya University* P. digitatum spores were exposed to oxygen radicals 10 and 20 mm downstream from our developed atmospheric-pressure oxygen-radical source. Treated spores were stained by 1,1′-dioctadecyl-3,3,Y,3′-tetramethyl indocarbocyanine perchlorate (DiI), which has been used for investigation for functions of cell membranes. For control spores, DiI is not permeable into cells because cell membranes have selective permeability. Stained spores were observed by confocal laser microscopy. At 10 mm distance, 84% of total spores were intracellularly stained with 1.5-minute oxygen radical treatment. On the other hand, at 20 mm distance, about 80% of the total spores were intracellularly stained at least with 3-minute oxygen radical treatment. Based on the results of inactivation rates of *P. digitatum* spores and oxygen-radical densities, the results indicated that the increase of ratio of the number of intracellularly stained spores was correlated with the density of $O(^3P_j)$ rather than $O_2(^1\Delta_g)$. These results and SEM observations suggest that $O(^3P_j)$ plays an important role as an inactivation factor by disturbing the normal function of cell membranes and influencing intracellular organelles without major deformation of the membranes.

MR1 54 Air surface microdischarge-photon synergy in antibacterial plasma-activated water* DAVID GRAVES, MATHEW PAVLOVICH, HUNG-WEN CHANG, YUKI SAKIYAMA, DOUGLAS CLARK, *UC Berkeley* We show that the antibacterial effects of air plasma on water can be amplified by synergy with ultraviolet (UV) photons. We use the surface microdischarge configuration (SMD) in atmospheric air adjacent to bacteria-laden water coupled with UVA (360 nm) photons from a light emitting diode (LED) to demonstrate this synergy. Air SMD, especially if operated in a

confined space, can operate in different modes: low power mode (<0.1 W/cm2) generates primarily O3 whereas higher powers generate mainly nitrogen oxides; we focus here on the latter. The nitrogen oxide mode creates a powerful antibacterial mixture in water, including NO2-, NO3- and H2O2. Although these species alone can be strongly antibacterial, especially at low pH, we show that addition of UVA photons greatly amplifies the antibacterial effect. We first measured log reductions with only photons and then only plasma. Only when UVA exposes water after plasma does the synergy appear. Synergy appears to be due to UVA photolysis of plasma-generated NO2- to form NO and OH. We conclude that combining plasma-generated chemical species with activating photons can amplify and strengthen plasma effectiveness in many biological and other applications.

MR1 55 The interaction of atmospheric pressure plasma jets with cancer and normal cells: generation of intracellular reactive oxygen species and changes of the cell proliferation and cell cycle* TAE HUN CHUNG, HEA MIN JOH, SUN JA KIM, SUN HEE LEEM, *Dong-A University* The possibility of atmospheric pressure plasmas is emerging as a candidate in cancer therapy. The primary role is played by reactive oxygen species (ROS), UV photons, charged particles and electric fields. Among them, intracellular ROS induced by plasma are considered to be the key constituents that induce cellular changes and apoptosis. In this study, the effects of atmospheric pressure plasma jet on cancer cells (human lung carcinoma cells) and normal cells (embryonic kidney cells and bronchial epithelial cells) were investigated. The plasma treatment was performed under different working gases, applied voltages, gas flow rates, and with and without additive oxygen flow. Using a detection dye, we observed that plasma exposure leads to the increase of the intracellular ROS and that the intracellular ROS production can be controlled by plasma parameters. A significant ROS generation was induced by plasma exposure on cancer cells and the overproduction of ROS contributes to the reduced cell proliferation. Normal cells were observed to be less affected by the plasma-mediated ROS and cell proliferation was less changed. The plasma treatment also resulted in the alteration of the cell cycle that contributes to the induction of apoptosis in cancer cells. The selective effect on cancer and normal cells provides a promising prospect of cold plasma as cancer therapy.

MR1 56 DNA damage induced by low energy electron collision and new experimental setup for further studying DNA damage by plasma YEUNSOO PARK, *National Fusion Research Institute* LEON SANCHE, RICHARD WAGNER, *University of Sherbrooke* Low energy electrons (LEEs; below 10 eV) are the most abundant among the radiolytic species generated along the high energy radiation track in living cell. And these electrons are also one of major components with ions and photon in plasma. Interestingly, it has turned out that LEEs can create DNA damages such as base release, single- and double- strand breaks (SSB and DSB) via indirect action named dissociative electron attachment (DEA). The purposes of this study are to further find out exact mechanisms of DNA damage by LEEs at the molecular level and to verify new DNA damage like structural alteration on DNA subunits. And we will expand our study to DNA damage by plasma source to develop plasma-based new medical and biological applications. We are currently setting

new experimental system for reaching our goals. We will show some recent results about new finding DNA modification damage and some experimental designs and working principles.

MR1 57 Low Temperature Plasma Kills SCaBER Cancer Cells NAZIR BAREKZI, LUCAS VAN WAY, MOUNIR LAROUSSI, *Old Dominion University* Squamous cell carcinoma of the bladder is a rare type of bladder cancer that forms as a result of chronic irritation of the epithelial lining of the bladder. The cell line used in this study is SCaBER (ATCC® HTB-3™) derived from squamous cell carcinoma of the human urinary bladder. Current treatments of bladder cancer include surgery, radiation and chemotherapy. However, the cost of these treatments, the potential toxicity of the chemotherapeutic agents and the systemic side-effects warrant an alternative to current cancer treatment. This paper represents preliminary studies to determine the effects of biologically tolerant plasma (BTP) on a cell line of human bladder cancer cells. Previous work by our group using the plasma pencil [1] revealed the efficacy of BTP on leukemia cells suspended in solution [2]. Based on these earlier findings we hypothesized that the plasma exposure would elicit a similar programmed cell death in the SCaBER cells. Trypan blue exclusion and MTT assays revealed the cell killing after exposure to BTP. Our study indicates that low temperature plasma generated by ionizing helium gas and the reactive species may be a suitable and safe alternative for cancer therapy.

[1]Laroussi M and Lu X. 2005. *Applied Physics Letters*, 87(113902):1–3.
[2]Barekzi N and Laroussi M. 2012. *Journal of Physics D: Applied Physics*. 45(42): p. 422002.

MR1 58 Atmospheric pressure dielectric barrier discharges interacting with liquid covered tissue* WEI TIAN, MARK J. KUSHNER, *University of Michigan* Tissue treated by atmospheric pressure dielectric barrier discharges in plasma medicine are often covered by a thin layer of liquid, water with dissolved gases and proteins. The liquid processes the plasma produced radicals and ions prior to their reaching the tissue. We report on a computational investigation of the interaction of DBDs with a thin liquid layer covering tissue. The simulations were performed with *nonPDP-SIM*, a 2-D plasma hydrodynamics and radiation transport model. The liquid is treated identically to the gas as a partially ionized substance but with a higher density. Liquid evaporates into the gas with a source given by its saturated vapor pressure. Transport of gas phase species into the liquid is determined by Henry's Law considerations. The tissue is treated as a dielectric and the species fluxes onto the tissue are recorded. The liquid layer, typically hundreds of microns thick, is water containing dissolved O_2 and alkane-like hydrocarbons (RH). In the model, the DBDs are operated with multiple pulses at 100 Hz followed by a 1 s afterglow. Gas phase reactive oxygen and nitrogen species (RONS) intersect the water vapor saturated air above the liquid and then solvate when reaching the liquid. The photolysis of water by plasma produced UV/VUV plays a significant role in the radical production. Without RH, O_2^- and hydronium (H_3O^+) dominate the water ions with H_3O^+ determining the pH. The dominant RONS in the liquid are O_3, H_2O_2, and HNO_x. With RH, ROS are largely consumed, leaving R(alkane radical) to reach the tissue.

MR1 59 The injection of microorganisms into an atmospheric pressure rf-driven microplasma* P.D. MAGUIRE, C.M.O. MAHONY, *University of Ulster* D. DIVER, *University of Glasgow* D.

MARIOTTI, *University of Ulster* E. BENNET, H. POTTS, *University of Glasgow* D.A. MCDOWELL, *University of Ulster* The introduction of living organisms, such as bacteria, into atmospheric pressure microplasmas offers a unique means to study certain physical mechanisms in individual microorganisms and also help understand the impact of macroscopic entities and liquid droplets on plasma characteristics. We present the characterization of an RF-APD operating at 13.56 MHz and containing microorganisms in liquid droplets emitted from a nebulizer, with the spray entrained in a gas flow by a gas shroud and passed into the plasma source. We report successful microorganism injection and transmission through the plasma with stable plasma operation of at least one hour. Diagnostics include RF electrical characterization, optical emission spectrometry and electrostatic deflection to investigate microorganism charging. A close-coupled Impedans Octiv VI probe indicates source efficiencies of 10 to 15%. The introduction of the droplets/microorganisms results in increased plasma conductivity and reduced capacitance, due to their impact on electron density and temperature. An electrical model will be presented based on diagnostic data and deflection studies with input from simulations of charged aerosol diffusion and evaporation.

MR1 60 Comparison of an APPJ discharge characteristics to internal properties of living cells* PIETRO RANIERI, SARAH GUCKER, JOHN FOSTER, ANIRUDDHA RAY, RAOUL KOPELMAN, LESHERN KARAMCHAND, *University of Michigan* Plasma medicine is quickly developing into a novel research field for decontamination and treatment for both wounds and disease. A common question between the research efforts is the effect of plasma both around the cell and within it. This study aims to discover the effect of an atmospheric pressure plasma jet on the internal properties of living cells as a function of treatment time. Through the use of nanoparticles, relative changes in pH and singlet oxygen both inside the cells and the cell media have been determined for various plasma exposure times. Further diagnostic tests on the plasma discharge will allow this effort to compare the results from changes inside the cell to those in the surrounding atmosphere to gain further insight on the reaction of the cell to plasma treatment.

MR1 61 Plasma jets for biomedical applications: PAPS control of the rare gas jets* JEAN-MICHEL POUVESLE, VANESSA SARRON, ERIC ROBERT, *GREMI, Orleans University/CNRS, France* JEROME FONTANE, *DAEP, ISAE/Toulouse University, France* THIBAULT DARNY, DELPHINE RIES, SEBASTIEN DOZIAS, *GREMI, Orleans University/CNRS, France* LAURENT JOLY, *DAEP, ISAE/Toulouse University, France* The development of atmospheric pressure plasma biomedical applications led number of teams to develop various types of rare gas plasma jets. It's generally thought that the plasma plume expanding in air, where most of the reactive species are produced, just follow the rare gas canal which is produced at the outlet of the plasma reactor capillary. Depending on Reynolds number (i.e. capillary diameter, gas flow rate), the rare gas flow will undergo a laminar or turbulent regime. This directly affects the reactive species distribution at the plasma/target interface, thus potentially having an influence on the realized treatment. In this work, not only we demonstrate that PAPS (Pulsed Atmospheric pressure Plasma Stream) production parameters (frequency, capillary length) directly affect the rare gas flow

structure in addition to flow parameters mentioned above, but that the PAPS themselves control the gas column development outside the capillary. At low flow rate, there exists a real build up of the gas column within the first hundred of pulses and a rapid return to initial situation as soon as the plasma is off. This allows a very precise modulation of plasma application. Conversely, it can lead to misinterpretations if not taken into account properly in the treatment protocol.

MR1 62 The electrodynamics of aerosols and bacteria in a microplasma* P.D. MAGUIRE, C.M.O. MAHONY, *University of Ulster* D. DIVER, *University of Glasgow* D. MARIOTTI, *University of Ulster* E. BENNET, H. POTTS, *University of Glasgow* D.A. MCDOWELL, *University of Ulster* The physics of living organisms is considered a grand challenge of science. Plasma interactions with living organisms, particularly at atmospheric pressure, offer a unique opportunity to study the physical mechanisms and surface electrodynamics of individual microorganisms. The impact on the plasma of such macroscopic entities is itself important; the dynamics of non-spherical and non-rigid nano-/micro-scale structures have received little attention. Also the plasma interaction with water, from molecules to droplets, is becoming increasingly significant due to induced chemistries that differ considerably from conventional plasma chemistry. We investigate the bulk and surface physical properties of individual microorganisms, particularly bacteria, through electrical and visco-mechanical excitation. Individual organisms are transported by water droplets to an rf microplasma. Their impact on the plasma is determined by imaging, optical and electrical diagnostics. We report, using imaging, electrostatics and simulation, on (i) fluid stability under evaporative stress of charged microbe-carrying macroscopic droplets, (ii) impact of the plasma on the stochastic component of motion and (iii) the acquired charge distribution and transfer from liquid to lipid surface.

MR1 63 Application of Surface Micro-Discharge plasma to spacecraft component decontamination* SATOSHI SHIMIZU, *Max-Planck-Institut für extraterrestrische Physik* SIMON BARCZYK, PETRA RETTBERG, *Deutsches Zentrum für Luft- und Raumfahrt e.V. Institut für Luft- und Raumfahrtmedizin* TETSUJI SHIMIZU, TOBIAS KLAEMPFL, JULIA ZIMMERMANN, *Max-Planck-Institut für extraterrestrische Physik* PETER WEBER, *Deutsches Zentrum für Luft- und Raumfahrt e.V., Raumfahrtmanagement* GREGOR MORFILL, HUBERTUS THOMAS, *Max-Planck-Institut für extraterrestrische Physik* In the field of extinct or extant extraterrestrial life research on other planets and moons, the prevention of biological contamination through spaceprobes is one of the most important requirements, and its detailed conditions are defined by the COSPAR planetary protection policy. Currently, a dry heat microbial reduction (DHMR) method is the only applicable way to satisfy the demand, which could, however, damage the sophisticated components like integrated circuits. In this study, cold atmospheric plasma based on the Surface Micro-Discharge technology was investigated for inactivation of different types of bacteria and endospores as an alternative method. After 90 min of plasma gas exposure, 3-6 log reductions were observed for the vegetative bacteria *Escherichia coli* and *Deinococcus radiodurans* and several types of bacterial endospores - including *Bacillus atrophaeus*, *B. safensis*, *B. megaterium*, *B. megaterium 2c1* and *B.*

thuringiensis E24. Furthermore, the applicability of the system for spacecraft decontamination was checked by studying the inactivation homogeneity, the temperature at the area of interest and the effects of the plasma gas exposure on different materials.

MR1 64 Applications of plasma sources for nitric oxide medicine* VICTOR VASILETS, *V.L. Talrose Institute for Energy Problems of Chemical Physics, RAS* ANATOLY SHEKHTER, *I.M. Sechenov First Moscow State Medical University* ALEXANDER PEKSHEV, *N.E. Bauman Moscow State Technical University* Nitric oxide (NO) has important roles in the function of many tissues and organs. Wound healing processes are always accompanying by the increase of nitric oxide concentration in wound tissue. These facts suggest a possible therapeutic use of various NO donors for the acceleration of the wound healing and treatment of other diseases. Our previous studies [1] indicated that gaseous NO flow produced by air-plasma generators acts beneficially on the wound healing. This beneficial effect could be caused by the mechanism involving peroxynitrite as an intermediate. As a result of mobilization of various antioxidant reactions more endogenous NO molecules become available as signaling molecules. to regulate the metabolic processes in wound tissue. In this paper different air plasma sources generated therapeutic concentrations of NO are discussed. The concentration of NO and other therapeutically important gas products are estimated by thermodynamic simulation. Synergy effects of NO with other plasma components are discussed as a factor enhancing therapeutic results. Some new medical application of plasma devices are presented.

*Advanced Plasma Therapies Inc.

MR1 65 HEAVY PARTICLE COLLISIONS

MR1 66 Enhancement of Limb Growth by Non-Thermal Plasma Generated Reactive Species* N. SHAINSKY, M. STEINBECK, G. FRIDMAN, A. FRIDMAN, G. FRIEDMAN, *Drexel University* T. FREEMAN, *Thomas Jefferson University* Introduction: The goal of this investigation was to examine the effect of Dielectric Barrier Discharge plasma on mouse autopod differentiation and growth. In this study we hypothesized that NT-plasma can be used to promote redox dependent changes in differentiation pathways and enhance developmental signaling? Methods: Approximately 1 hour after isolation, NT-plasma or sham plasma treatment was applied to the right or left limb, respectively. The medium was changed daily thereafter for the 4-6 days of culture. NT-plasma treatment: pulsed (1000 Hz) voltage of 17 - 25 kV magnitude (peak to peak), a 1 μs pulse width and a rise time of 5 V/ns between the quartz-insulated high voltage electrode and the sample undergoing treatment. Results: A single 10 second NT-plasma treatment promoted development of mouse autopods as compared to the sham control contralateral limb. NT-plasma accelerated digit growth in both E14.5 and E12.5 autopods. Inhibitors were used to determine the role of ROS and RNS in mediating NT-plasma accelerated autopod development. Treatment with these agents stunted autopod morphogenesis NT-plasma treatment partially rescued development. Discussion: Our findings highlight the capability of NT-plasma to activate ROS-dependent cell signaling cascades within developing autopod tissue. In fact, the effect of NT-plasma may

indeed extend beyond ROS sensitive signaling as NT-plasma exposure seems to stimulate some growth even in the presence of antioxidant induced stunting.

MR1 67 Mean-field description of B^{2+}-Ne collisions with active target and projectile electrons* TOM KIRCHNER, GERALD SCHENK, MARKO HORBATSCH, *Department of Physics and Astronomy, York University, Toronto ON M3J1P3, Canada* We apply an independent electron model to study q-fold target charge state production in 25–600 keV/u B^{2+}- Ne collisions. Projectile and target electrons are treated on the same footing using a common potential and a single-determinant wave function for the combined system [1]. For the sake of comparison we also perform a reduced calculation in which the projectile electrons are frozen in their initial state. Results are compared with recent experimental and theoretical data for positive ion production as well as for Ne^{q+} production obtained in coincidence with an unchanged projectile charge state [2]. We find that the total cross sections obtained from our full calculation agree well with experiment for $q - 1, \ldots, 4$, while the reduced calculation produces pronounced discrepancies for $q \geqslant 2$. This suggests that the projectile electrons participate actively even in processes, in which the projectile charge state does not change. At the conference, we will demonstrate that direct projectile electron loss with and without simultaneous transfer of a target electron can explain the observed features.

[1] T. Kirchner and M. Horbatsch, Phys. Rev. A **63**, 062718 (2001).
[2] W. Wolff *et al.*, Phys. Rev. A **84**, 042704 (2011).

MR1 68 Synthesis and characterization of SnS2 ARTURO MENDEZ, *CINVESTAV* MAURICIO ORTEGA, JORGE CONTRERAS, *CINVESTAV, BUAP* Tin disulfide (SnS_2) nanoparticles were successfully prepared by colloidal chemistry using the hot-injection approach, starting of tin(II) chloride, sulfur and oleylamine. The phase composition and morphology were analyzed by X-ray diffraction, Raman spectroscopy and scanning electron microscopy (SEM). The results show that the synthesis produces nearly-spherical SnS_2 nanoparticles around 20-50 nm in size, crystallizing in the hexagonal structure. The elemental analysis carried out by EDAX indicated that the obtained nanoparticles are nearly stoichiometric SnS_2. A representative Raman spectrum reveals a sharp peak at 313 cm^{-1}, which characterizes the hexagonal phase of SnS_2.

MR1 69 Basis-generator-method study of ionization and fragmentation of water molecules by multiply-charged ion impact* TOM KIRCHNER, M. HORBATSCH, *Department of Physics and Astronomy, York University, Toronto, ON M3J1P3, Canada* M. MURAKAMI, *Department of Physics, National Taiwan University, Taipei 10617, Taiwan* T. PAUSZ, H.J. LÜDDE, *Institut für Theoretische Physik, Goethe-Universität, D-60438 Frankfurt, Germany* In a recent series of publications we have described the adaptation of the basis generator method (BGM), originally developed for ion-atom collisions, to molecular targets and have reported on results for proton and He^+-ion impact on H_2O molecules [1]. The microscopic collision calculations were complemented with a semi-phenomenological fragmentation model [2], which in contrast to previous models takes multiple electron removal processes

into account. This turned out to be crucial for obtaining reasonable agreement with experimental data for the production of singly charged fragment ions. In this contribution, we report on results obtained from using the same methodology for bare helium, lithium, and carbon ion impact on H_2O in the 20–5000 keV/amu regime and compare them with experimental data and previous calculations where available. In addition, we will discuss the usefulness of ternary plots [3] to provide a somewhat more general view on fragmentation in ion-water-molecule collisions.

[1]M. Murakami *et al.*, Phys. Rev. A **85**, 052704 (2012); **86** 022719 (2012).
[2]M. Murakami *et al.*, Phys. Rev. A **85**, 052713 (2013).
[3]E. C. Montenegro, J. Phys.: Conf. Ser. **194**, 012049 (2009).

MR1 70 Numerical simulations of N_2-N_2 quasi-complex formation in binary collisions ANATOLY NAPARTOVICH, *Retired* ALEXANDER KURNOSOV, *SRC RF TRINITI* CENTER FOR THEORETICAL PHYSICS AND NUMERICAL SIMULATIONS TEAM* It's known that atomic and molecular collisions in a gas at low temperatures may result in formation of the unstable quasi -complexes (QC). The specific feature of these complexes is rather long life time. The QCs are of interest for researchers since they can play an active role in various physical and chemical processes. Stabilization of a QC results in formation of molecular dimer. Numerical simulation of dynamics of the QCs requires detailed data about interaction potential. In particular, in [1] studies were done on sensitivity of the characteristics of Ar-CO_2 QC to a form of potential energy surface. No information exists about dynamics of bimolecular QCs. The purpose of our study is numerical simulations of a QC formation in bimolecular collisions. Of particular interest is formation of N_2-N_2 QC since the molecular nitrogen is the widespread species. We used the semi-classical coupled-state method described in [2] with the same intermolecular potential function. The rate constants for the N_2-N_2 QC formation will be presented.

[1]S. V. Ivanov, Molecular Physics, 2004, v.102, p. 1871.
[2]M. Cacciatore, A. Kurnosov, A. Napartovich, Journal of Chemical Physics, 2005, v.123, p. 174315.

MR1 71 DISSOCIATION, RECOMBINATION AND ATTACHMENT

MR1 72 Computational Study on Chemical Reaction Properties of C_4F_8 Plasma Molecules HEECHOL CHOI, *National Fusion Research Institute (NFRI)* YOUNG C. PARK, *Korea Advanced Institute and Technology (KAIST)* KYOUNG K. BAECK, *Gangneung-Wonju National University (GWNU)* YOON S. LEE, *Korea Advanced Institute and Technology (KAIST)* FUNDAMENTAL TECHNOLOGY RESEARCH DIVISION TEAM,* DEP. OF CHEMISTRY TEAM,† DEP. OF CHEMISTRY TEAM‡ Of many perfluorocarbons(PFCs), C_4F_8 species attract special attention because of their potential for decreasing global warming gas emissions and their high CF_2 radical levels in commercial plasma treatments. Several experimental and theoretical studies of these species have been conducted, although only the geometries at their stationary states and their adiabatic electron affinities have been determined. However, this information is not sufficient for a deep understanding of all the possible fates and roles of C_4F_8 species and their fragments in plasma phases. So a careful additional assessment of the reliability of DFT functionals for the study of PFCs is highly required. First, in order to find a DFT method appropriate to PFCs, the geometry, energy, and chemical reaction properties of C_4F_8 were calculated and compared with reference data. Second, based on variational transition-state theory, the rate constants of dissociations and isomerizations of C_4F_8 species were computed for a deep insight into their mechanisms.

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MR1 73 Dissociative electron attachment to the monocyclic azines pyrimidine, pyridazine, pyrazine and 1,3,5-triazine THOMAS GILMORE, THOMAS FIELD, NATHAN AGNEW, *Centre for Plasma Physics, Queen's University Belfast, BT71NN, Northern Ireland* ANDREAS MAURACHER, SAMUEL ZÖTTL, *Institute of Ion Physics and Applied Physics, University of Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria* EWELINA SZYMANSKA, *Department of Physics and Astronomy, The Open University, Walton Hall, MK76aA, United Kingdom* Observations of dissociative electron attachment to Pyrimidine, Pyrazine, Pyridazine ($C_4H_4N_2$) and 1,3,5-Triazine ($C_3H_3N_3$) are reported in the electron energy range 0-12eV. Pyrimidine is the building block of the nucleobases Cytosine, Thymine and Uracil. Dissociation of the nucleobases caused by low energy electrons, eg. released by the Auger effect in radiation therapy, has been studied over the last decade. Resonances presented here will be compared to those observed in nucleobase experiments. CN^- is identified as the main product of dissociative electron attachment to the azine molecules. Resonances occur near 5.1 eV and 8.2 eV for all molecules. A comparison to R-matrix calculations by Masin and Gorfinkiel show reasonable agreement to experiment. Absolute cross sections for dissociative electron attachment have been estimated: pyrimidine has a maximum negative ion formation cross section of 8 × 10^{-3} Å^2 at 5.1 ± 0.2 eV. The cross sections on resonance for negative ion formation in dissociative electron attachment to the other molecules are all within a factor of two of this peak value for pyrimidine. The absence of hydrogen fragments, reported as dominant in nucleobase studies, is also investigated.

MR1 74 DISTRIBUTION FUNCTIONS AND TRANSPORT COEFFICIENTS FOR ELECTRONS AND IONS

MR1 75 Updates on the freeware electron Boltzmann equation solver BOLSIG+ G.J.M. HAGELAAR, L.C. PITCHFORD, *LAPLACE, CNRS and University of Toulouse, France* In 2005, we released BOLSIG+, a user-friendly and free computer application solving the Boltzmann equation for electrons in uniform electric fields in order to obtain electron transport coefficients and rate coefficients from cross section data. The physical principles of BOLSIG+ were described in a journal article [Plasma Sources Sci. Technol. 14, 722-733 (2005)]. Since then BOLSIG+ has grown into a standard tool in research on collisional gas discharges. This paper discusses a number of BOLSIG+ extensions/improvements that were added over the years but were never published in the official literature, including anisotropic diffusion coefficients. We also

show comparisons with Monte-Carlo calculations in order to evaluate possible errors due to the two-term approximation (of the angular dependence of the distribution function) used by BOLSIG+. These errors are smaller than is generally thought and are in fact insignificant over a wide range of conditions, provided that proper attention is paid to the consistency of the input data and the definition of the transport coefficients.

MR1 76 Electron swarm transport coefficients in H2O - He mixtures: Experiment and calculations* J. DE URQUIJO, A.M. JUÁREZ, *Instituto de Ciencias Físicas, UNAM, México* J.L. HERNÁNDEZ-ÁVILA, E. E. BASURTO, *Departamentos de Energía y Ciencias Básicas, Universidad Autónoma Metropolitana, México* K.F. NESS, R.E. ROBSON, RON WHITE, *ARC Centre for Antimatter-Matter Studies, School of Engineering and Physical Sciences, James Cook University, Townsville, Australia* M.J. BRUNGER, *ARC Centre for Antimatter-Matter Studies, School of Chemical and Physical Sciences, Flinders University, Adelaide, Australia* In this presentation we report recent measurements of electron swarm transport coefficients using the pulsed-Townsend technique for mixtures of water and helium over the range of applied fields E/N from 0-200Td. Comparison is made with transport coefficients calculated using a multi-term Boltzmann equation solution and recently proposed electron-water cross-section sets. This represents a new and more discriminative test on the accuracy and consistency of such sets. Negative differential conductivity is observed for a small window of mixture ratios, even though the pure gases themselves do not demonstrate NDC. Similar interesting effects are observed in the ionization rates as a function of the mixture ratios. The origin of these behaviours will be discussed.

MR1 77 OTHER ATOMIC AND MOLECULAR COLLISION PHENOMENA

MR1 78 Momentum transfer cross sections for the heavy noble gases ALLAN STAUFFER, *Department of Physics and Astronomy, York University, Toronto, Canada* ROBERT MCEACHRAN, *CAMS, Research School of Physics and Engineering, Australian National University, Canberra, Australia* We have used our relativistic optical potential method [1] to calculate the momentum transfer cross sections for Ar, Kr and Xe from threshold to 1000 eV. The target ground state as well as the open excited and ionization channels used in the optical potential have been calculated using the MCDF program [2]. We have included 17 excitation channels for Ar, 26 for Kr and 15 for Xe. In the ionization channels, ionization of the outer p, s and d shells were included for Kr and Xe while for Ar all electrons were allowed to be ionized. Comparisons with previous calculations and experimental measurements will be included. We also include analytic fits to our cross sections to aid in plasma modelling studies.

[1] S. Chen, R. P. McEachran, and A. D. Stauffer, J. Phys. B **41**, 025201 (2008).

[2] I. P. Grant, B. J. McKenzie, P. H. Norrington, D. F. Mayers, and N. C. Pyper, Comput. Phys. Commun. **21**, 207 (1980).

MR1 79 Static potentials for electron-molecule scattering: the case of water ALLAN STAUFFER, *Department of Physics and Astronomy, York University, Toronto, Canada* TAPASI DAS, RAJESH SRIVASTAVA, *Department of Phyics, Indian Institute of Technology, Roorkee, India* Molecular wave functions are commonly represented by Gaussian orbitals which have a simple form. We have derived a scheme to calculate spherically-averaged static potentials for electron-molecule scattering which is analytic except for the inclusion of the error function which can be easily calculated using existing algorithms. Although the asymptotic form of these potentials falls off too rapidly, the scattering potential is dominated by the long range polarization potential in this region. Including an exchange potential produces a result which is realistic representation of the electron-molecule interaction. Details of the method will be presented as well as an application to electron scattering from water. Our method produces results in good agreement with existing calculations and experimental measurements. The extension of this method to more complex molecules is straightforward.

MR1 80 Two-center approach to fully differential positron-impact ionisation of hydrogen* A.S. KADYROV, I. BRAY, *Curtin University* The two-center approach to positron-impact ionisation of atomic hydrogen is shown to follow from the exact *post* form of the breakup amplitude [Kadyrov *et al.*, Phys. Rev. Lett. **101**, 230405 (2008)]. In such approaches distinct ionization amplitudes arise from each center for the same ionization process. The fully differential cross section for positron-impact breakup of atomic hydrogen is calculated including direct ionisation of the target and electron capture into the positronium continuum. We show that the coherent combination of the amplitudes leads to unphysical oscillations in the differential cross sections, whereas the incoherent combination does not. On this basis it is concluded that two-center approaches to the problem should assume incoherent combination of the amplitudes from direct ionisation of the atom and positronium formation in the continuum. The latter is also consistent with the unitarity of the close-coupling formalism.

MR1 81 Monte Carlo simulation of rotating wall positron cloud compression* SRDJAN MARJANOVIC, ANA BANKOVIC, MILOVAN SUVAKOV, SASA DUJKO, ZORAN LJ. PETROVIC, *Institute of Physics, Pregrevica 118, 11080 Belgrade, Serbia* We have used our standard Monte Carlo code and applied it to electric potential setup that models the conditions inside the rotating wall apparatus. This model has allowed us to investigate the mechanisms behind the compression and to determine the types of collisions responsible for compression. Our results show that both "high threshold" losses, like ionization or electronic excitation, as well as "low threshold" losses, like vibrational and rotational excitations, play a role in compression. Parts of the positron ensemble that are further away from the axis are heated by the rotating field much stronger than the particles that are closer. Without the "high threshold" processes trajectories of these particles become unstable after several collisions. On the other hand, these "high threshold" processes do not provide strong enough cooling for fast compression. That is why "low threshold" processes are necessary to compress the positron beam to widths several orders of magnitude smaller. In addition we will report on frequency scan for compression rates,

as well as compression rates for different values of the applied rotating electric field, magnetic field, and background gas pressure conditions.

MR1 82 Correlated $n^{1,3}$S states for two-electron atoms in screened potentials LORENZO UGO ANCARANI, *Universite de Lorraine, France* KARINA V. RODRIGUEZ, GUSTAVO GASANEO, *Universidad Nacional del Sur, Argentina* We investigate two-electron atoms placed in a plasma environment, and consider both exponential cosine screened Coulomb potentials (ESCP) [1] and Debye-Hückel or screened Coulomb potentials (SCP), for which the screening parameter λ is related to the plasma frequency. Using highly correlated Hylleraas-type expansions, Ghoshal and Ho [2] have published the first calculations of the ground states of H^- and He in ECSCP and SCP for a wide range of λ values. We have confirmed these results with relatively simpler wave functions within a Configuration Interaction approach with explicitly correlated basis functions satisfying exactly all two-body Kato cusp conditions [3]. The main aim of the present contribution is to extend the findings of Ghoshal and Ho in various directions: (i) we evaluate the energy for the ground and the first ^{1,3}S excited states, and provide analytical fits of the energy $E(\lambda)$; (ii) we further extend the investigation to the iso-electronic series considering higher values of the nuclear charge Z and provide a double fit $E(\lambda,Z)$ – thus a practical estimation tool for plasma applications; (iii) we make a systematic investigation of the λ_0 value for which the ground state ceases to exist.

[1] P K Shukla and B Eliasson 2008 Phys. Lett. A **372**, 2897.
[2] A Ghoshal and Y K Ho 2009 J. Phys. B **42**, 075002; **42**, 175006.
[3] L U Ancarani and G Gasaneo 2007 Phys. Rev. A **75**, 032706; 2008 Phys. Rev. A **77**, 012705.

MR1 83 Positron transport in gases in electric and magnetic fields crossed at arbitrary angles ANA BANKOVIC, SASA DU-JKO, SRDJAN MARJANOVIC, *Institute of Physics, Pregrevica 118, 11080 Belgrade, Serbia* RONALD D. WHITE, *ARC Centre for antimatter-Matter Studies, School of Engineering and Physical Sciences, James Cook University, Townsville 4810, Australia* ZORAN LJ. PETROVIC, *Institute of Physics, Pregrevica 118, 11080 Belgrade, Serbia* The knowledge of positron transport in gases under the influence of electric and magnetic fields is of key importance in optimizing positron traps. In this work we apply a multi term solution of Boltzmann's equation to study positron transport in gases under the influence of electric and magnetic fields crossed at arbitrary angles. Calculations are performed over a range of E/N and B/N values, and angles between the fields for positrons in N2, H2 and H2O. Values of mean energy, drift velocity, diffusion tensor, energy gradient vector, and temperature tensor and rate coefficient for positronium (Ps) formation are reported in this work. It is demonstrated that the difference between the bulk and flux transport coefficients resulting from the explicit effects of Ps formation can be controlled either by the variation in the magnetic field strengths or by the angles between the fields. Special attention is paid to synergistic effects of Ps formation and angle between the fields on the Ps-induced NDC phenomenon for positrons in H2 and H2O. The results presented in this work represent the first multi term solution of the non-conservative Boltzmann equation for positrons in varying configurations of electric and magnetic fields.

MR1 84 Quasi-Sturmian approach to two- and three-body continuum Coulomb problems JESSICA A. DEL PUNTA, MARCELO J. AMBROSIO, GUSTAVO GASANEO, *Universidad Nacional del Sur, Argentina* LORENZO UGO ANCARANI, *Universite de Lorraine, France* DARIO M. MITNIK, *IAFE, Buenos Aires, Argentina* S.A. ZAYTSEV, M.S. ALESHIN, *Khabarovsk, Russia* In this work we present new two-body basis functions to be used when solving atomic physics scattering problems. We name them Quasi Sturmian (QS) because of the resemblance of their generating equation with that of Generalized Sturmian (GS) sets [1]. They can be thought of a generalization of the Green function as they satisfy a non-homogeneous Schrödinger equation where the delta function is replaced by any element of a L^2 basis set. The QS functions are regular at the origin, form a complete basis set with scattering asymptotic form and, by construction, solve the interactions appearing in the original Schrödinger equation. Once a set of QS is generated, it can be used to expand a scattering solution. In comparison with well established GS functions, our numerical investigations showed that the proposed QS possess convergence superiority. Initially set for two-body interactions, the proposal can be easily extended to three-body problems. For a two-body Coulomb scattering problem, and taking Laguerre basis functions as L^2 basis set, the QS functions can be expressed analytically. As a consequence, when QS are applied to three-body scattering calculations, analytical expressions result for all necessary matrix elements. Furthermore, the properties of the two-body basis functions allow one for an analytical study of the three-body wave function itself.

[1] Mitnik *et al.*, Comp. Phys. Comm. **182**, 1145 (2011).

MR1 85 Modeling Positron Transport in Gaseous and Soft-condensed Systems with Kinetic Theory and Monte Carlo* G. BOYLE, W. TATTERSALL, R.E. ROBSON, RON WHITE, *ARC Centre for Antimatter-Matter Studies, School of Engineering and Physical Sciences, James Cook University, Townsville* S. DUJKO, Z. LJ. PETROVIC, *Institute of Physics, University of Belgrade, Zemun, Belgrade, Serbia* M.J. BRUNGER, *ARC Centre for Antimatter-Matter Studies, School of Chemical and Physical Sciences, Flinders University, Adelaide, Australia* J.P. SULLIVAN, S.J. BUCKMAN, *ARC Centre for Antimatter-Matter Studies, Research School of Physical Sciences, Australian National University, Canberra, Australia* G. GARCIA, *Instituto de Fisica Fundamental, Consejo Superiorde Investigaciones Cientificas, Madrid, Spain* An accurate quantitative understanding of the behavior of positrons in gaseous and soft-condensed systems is important for many technological applications as well as to fundamental physics research. Optimizing Positron Emission Tomography (PET) technology and understanding the associated radiation damage requires knowledge of how positrons interact with matter prior to annihilation. Modeling techniques developed for electrons can also be employed to model positrons, and these techniques can also be extended to account for the structural properties of the medium. Two complementary approaches have been implemented in the present work: kinetic theory and Monte Carlo simulations. Kinetic theory is based on the multi-term Boltzmann equation, which has recently been modified to include the positron-specific interaction processes of annihilation and positronium formation. Simultaneously, a Monte Carlo simulation code has been developed that can likewise incorporate positron-specific processes.

MR1 86 A Review of recent theoretical development for Coulomb explosion and stopping power of energetic molecular ions and clusters in plasmas* GUIQIU WANG, *Dalian Maritime University* YOUNIAN WANG, *Dalian University of Technology* We summarize our recent theoretical study for Coulomb explosion and stopping power of energetic molecular ions and clusters in

plasmas. It's an interesting topic because the potential use of cluster ion beams in fusion research. In particular, there exists a promising inertial confinement fusion scheme in which a plasma target is radiated simultaneously by both an intense laser beam and an intense ion beam. In this paper, the emphasis is laid on the dynamic polarization and correlation effects of the constituent ions within the cluster in order to disclose the role of the vicinage effects on the Coulomb explosion and energy deposition of the molecules and clusters in plasma. On the other hand, affecting of a strong laser field on the cluster propagating in plasma is considered, the influence of a large range of laser parameters and plasma parameters on the Coulomb explosion and stopping power are discussed. Furthermore, in order to indicate the effects of different cluster sizes on the stopping power, a comparison is made for hydrogen clusters and carbon clusters. In addition, the deflection of molecular axis for diatomic molecules during the Coulomb explosion are also discussed for the cases both in the presence of laser field and laser free.

MR1 87 Neutral Resonant Ionization in Hydrogen Anion Production JOHN VOGEL, *University of California (retired)* Dissociative ionization of molecules causes gas phase H^- but fails to explain anion intensity. Atomic collisions on surfaces with reduced work function give anions, but also fail to explain intensity, lowered electron density, and diagnostics. Neutral resonant ionization of $H(2s)$ atoms to ion pairs is here predicted with a very high cross section. $H(2s,p)$ atoms are resonant with numerous short-lived excited states ("resonances") of H^- as well as the putative doubly-excited stable state of H^- which resists production by other means. This state decays through $^1\Sigma_u^+$ ($2s\ \sigma_u^2$) to a singly excited ion pair, leaving both proton and anion with 3.8 eV energy. $H(2s,p)$ atoms arise from dissociative recombination of trihydrogen ion (H_3^+) which dominates ion content of hydrogen plasmas. Initial $H(2s,p)$ are resonantly produced by ground state Cs atoms or excited Ar, Kr, and Xe atoms, but these initiators are not needed to sustain anion production. This theory may explain the intense ion source at Cal Tech that produced 1.5 mA/cm^2 H_3 in the mid-1980's (1). A full CRM calculation is not complete, but equilibrium calculations suggest that >1 mA/cm^2 H^- may be predicted.

[1]J. F. Garvey and A. Kuppermann, Rev. Sci. Instrum. **57**, 1061 (1986).

MR1 88 POST-DEADLINE ABSTRACTS

MR1 89 Soliton and Double layer in multi-component plasma. KARIMA ANNOU, NADIA SAOULA, RABAH TADJINE, *cdta* In the present work, an investigation of double layer formation in four-component plasmas is made. Assuming that the constituents of plasma are electrons, ions, and an admixture of dynamics ions with negative and positive charge. It is shown that stationary solutions of the fluid equation combined with Poisson's equation can be expressed in terms of the energy integral of a classical particle with a Sagdeev Potential. Furthermore, the four-fluid plasma system provides the possibility of generation of ion acoustic solitary waves (namely: Solitons), as well as double layers. Additionally, conditions under which double layer arise are given, and their profiles are display graphically.

MR1 90 Self-organized electrode processes in the carbon arc discharge for nanotube synthesis* JONATHAN NG, YEVGENY RAITSES, *PPPL* The atmospheric pressure carbon arc in helium is an important method for nanotube production [1]. Typical arcs operate in a dc mode between a graphite anode, which is consumed, and a lower melting temperature cathode (e.g. copper [2, 3]). It is accepted that electrons from the cathode are emitted by thermionic field emission [2,4], requiring the cathode to be above the melting temperature of its material. Yet, the cathode usually remains undamaged by the arc, raising the question about how the electron current in the arc is supported. Our experiments with copper, stainless steel and aluminum cathodes have revealed that thermo-field emission is the source of most of the arc current at the cathode, but emission is from the carbon deposit formed on the cathode in the course of the arc operation. Due to its low heat conduction, the cathode does not reach its melting temperature and remains undamaged. The evaporation of the graphite anode and formation of the carbon deposit on the cathode are self-organized to maintain the current conduction in the arc.

[1]Journet *et al.*, Nature 388:756 (1997).
[2]Keidar and Beilis, J. Appl. Phys. **106**, 103304 (2009).
[3]Fetterman *et al.*, Carbon **46**, 1322 (2008).
[4]Hantzsche, Beitr. Plasmaphys. **22**, 325 (1981).

MR1 91 Measurement of negative ion mobility with a trace moisture analyzer in O_2 YUI OKUYAMA, SUSUMU SUZUKI, HARUO ITOH, *Chiba Institute of Technology* We have been investigated the effects of impurities on the negative ion mobility in O_2 at high pressures including atmospheric pressure using a high-pressure ion drift tube with a positive point plate gap that acts as a negative ion detector [1]. When a small admixture of impurities such as N_2 and CO_2 from atmosphere are existed in O_2, negative ion mobility is increased at $E/N > 1.77$ Td due to formations of NO_2^-, NO_3^-, CO_3^-, CO_4^- as impurity ions. In addition, existence of H_2O in O_2 leads to decrease negative ion mobility because $O_2^- \cdot (H_2O)_n$ forms by ion-molecule between O_2^- or O_4^- and H_2O [2]. In this work, we describe the experimental results on the measurement of negative ion mobility in ultrahigh-purity O_2 with a trace moisture analyzer (HALO-H_2O). The ion drift tube is mounted in the stainless steel chamber with stainless steel pipes to connect the trace moisture analyzer and O_2 bottle of 99.99995% purity with a gas defecator (MICROTORR: MC200-203). Mobility measurements were carried out after gas flowing, baked and pumped the chamber and gas lines at least two months due to remove impurities. During the measurements, O_2 were flowed through the chamber at 0.5 L/min. As the results, a constant mobility 2.39 cm^2/V$\cdot$s was observed at H_2O concentration between 30 and 100 ppb. This value is good agreement with the polarization limit of mobility for O_4^-.

[1]Y. Okuyama *et al.*, J. Phys. D: Appl. Phys. **45**, 195202 (2012).
[2]Y. Okuyama *et al.*, 65th Annual Gaseous Electronic Conference, 57, 8, MW2.00006 (2012).

MR1 92 Magnetically insulated baffled probe for measurements in complex magnetized plasma diagnostics* CHENGGANG JIN, RAITSES YEVGENY, *Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA* VLADIMIR DEMIDOV, *Department of Physics, West Virginia University, Morgantown, West Virginia 26506, USA* When the magnetic field is parallel to the probe surface, the electron-repelling sheath can be significantly reduced as the magnetic field also impedes the cross-field electron flow and therefore, a smaller sheath voltage is needed to maintain the zero current balance to the floating probe. This is the basic

idea of the magnetically insulated baffled (MIB) probe, which offers the advantages of direct measurements of the plasma potential in magnetized plasmas while being non-emitting and electrically floating [1]. A simplified MIB probe was constructed by retracting the conducting pin of a classical Langmuir probe inside an insulating tube placed perpendicular to the magnetic field lines. The retracting distance of the collector inside the ceramic tube was calculated assuming classical and anomalous mechanisms of the electron cross-field diffusion and taking into account particles losses inside the tube. The results of MIB probe measurements in a Penning-type cross-field discharge are presented.

[1] V. I. Demidov *et al.*, Rev. Sci. Instrum. **81**, 10E129 (2010).

MR1 93 Simultaneous Filtered and Unfiltered Light Scattering Measurements in Laser Generated Air Sparks* CHRISTOPHER LIMBACH, RICHARD MILES, *Princeton University* Elastic laser light scattering may be used to measure the thermofluidic properties of gases and plasmas, including but not limited to density, temperature and velocity. Most of this information is contained within the spectra of the scattered radiation. This may be measured directly through dispersion or indirectly, by passing the light through an atomic or molecular vapor filter with known absorption features. In this work, filtered and unfiltered laser light scattering is used to diagnose air sparks generated by a 1064 nm Q-switched laser. The probe laser consists of a second Q-switched Nd:YAG laser frequency doubled to 532 nm. Simultaneous unfiltered and filtered images of the scattering are captured by a Princeton Instruments ICCD camera by using a 50 mm diameter concave re-imaging mirror. The filter consists of a well-characterized molecular Iodine cell. In the shock wave formed by the laser spark, spatially resolved measurements of density, temperature and radial velocity are extracted and compared with theory and models. Measurements in the spark core probe the ion feature of the electron Thomson scattering, from which n_e and T can be extracted with the assumption $T_e = T_i$.

MR1 94 Sheath induced instabilities in plasmas with E0 x B0 drift ANDREI SMOLYAKOV,* WINSTON FRIAS,† *University of Saskatchewan* IGOR KAGANOVICH,‡ YEVGENY RAITSES,§ *Princeton Plasma Physics Laboratory* It is shown that ion acoustic waves in plasmas with $\mathbf{E}_0 \times \mathbf{B}_0$ electron drift become unstable due to the closure of plasma current in the chamber wall. Such unstable modes may enhance both near-wall conductivity and turbulent electron transport in plasma devices with $\mathbf{E}_0 \times \mathbf{B}_0$ electron drift and unmagnetized ions. It is shown that the instability is sensitive to the wall material: a high value of the dielectric permittivity (such as in metal walls) reduces the mode growth rate by an order of magnitude but does not eliminate the instability completely.

*Professor, Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon SK, Canada.
†Graduate student, Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon SK, Canada.
‡Research Physicist, Princeton Plasma Physics Laboratory, Princeton NJ, USA.
§Research Physicist, Princeton Plasma Physics Laboratory, Princeton NJ, USA.

MR1 95 Plasma-induced crystallization of silicon nanoparticles* NICOLAAS KRAMER, REBECCA ANTHONY, MEENAKSHI MAMUNURU, ERAY AYDIL, UWE KORTSHAGEN, *University of Minnesota* The ability to form crystalline group IV nanoparticles makes plasma synthesis an attractive production mechanism. However, temperatures that are significantly higher than the gas temperature are required for crystallization of these materials to occur. The nanoparticle heating mechanism therefore remains one of the poorly understood aspects of the plasma synthesis technique. In the current study, we investigate the crystallization of nanoparticles using a tandem plasma configuration, characterizing both the nanoparticles and the plasma. Amorphous silicon nanoparticles, 3-5 nm in diameter, are formed in a low-power upstream plasma and then injected directly into a separate secondary plasma which is operated with variable power. *Ex situ* characterization of the nanoparticles using X-ray diffraction, Raman spectroscopy and transmission electron microscopy showed that crystallization occurs at powers of 20 W to 40 W, depending on the nanoparticle size. The second step is an in-depth plasma characterization. We performed optical emission spectroscopy on the secondary plasma to obtain the electron temperature and hydrogen density, and capacitive probes for ion density measurements during nanoparticle crystallization. These plasma conditions are used in a nanoparticle heating model to simulate the nanoparticle heating in the second plasma. Calculations show that nanoparticles obtain temperatures much higher than the gas temperature.

SESSION NR1: DIAGNOSTICS I
Thursday Morning, 3 October 2013; Room: Ballroom I at 10:00; Richard Miles, Princeton University, presiding

Invited Papers

10:00
NR1 1 Temperature diagnostics of a non-thermal plasma jet at atmospheric pressure* JAN SCHÄFER, *Leibniz Institute for Plasma Science and Technology Greifswald*

The study reflects the concept of the temperature as a physical quantity resulting from the second thermodynamic law. The reliability of different approaches of the temperature diagnostics of open non-equilibrium systems is discussed using examples of low temperature atmospheric pressure discharges. The focus of this work is a miniaturized non-thermal atmospheric pressure plasma jet for local surface treatment at ambient atmosphere [1]. The micro-discharge is driven with a capacitively coupled radio frequency electric field at 27.12 MHz and fed with argon at rates of about 1 slm through the

capillary with an inner diameter of 4 mm. The discharge consists of several contracted filaments with diameter around 300 μm which are rotating azimuthally in the capillary in a self-organized manner. While the measured temperatures of the filament core exceed 700 K, the heat impact on a target below the plasma jet remains limited leading to target temperatures below 400 K. Different kinds of temperatures and energy transport processes are proposed and experimentally investigated. Nevertheless, a reliable and detailed temperature diagnostics is a challenge. We report on a novel diagnostics approach for the spatially and temporally resolved measurement of the gas temperature based on the optical properties of the plasma [2]. Laser Schlieren Deflectometry is adapted to explore temperature profiles of filaments and their behaviour. In parallel, the method demonstrates a fundamental Fermat's principle of minimal energy. Information acquired with this method plays an important role for the optimization of local thin film deposition and surface functionalization by means of the atmospheric pressure plasma jet.

[1]Schäfer *et al.*, Eur. Phys. J. D **60**, 531 (2010).
[2]Schäfer *et al.*, Rev. Sci. Instrum. **83**, 103506 (2012).

Contributed Papers

10:30
NR1 2 Investigation of plasma densities in noble gas discharges by THz Time Domain Spectroscopy STEFFEN MARIUS MEIER, TSANKO VASKOV TSANKOV, DIRK LUGGENHÖLSCHER, UWE CZARNETZKI, *Institute for Plasma and Atomic Physics, Ruhr-University Bochum, Germany* Terahertz Time Domain Spectroscopy (THz TDS) is a non-invasive diagnostic method using ultra-short ($\sim$ps) radiation pulses with a broad spectral width ($\sim$0.1-5 THz) in the far-infrared region of the electromagnetic spectrum. Here this novel technique is applied to the determination of electron densities in low-temperature plasmas. The technical requirements will be introduced and advantages and challenges will be discussed. A new analysis method allows dealing with an inherent artefact resulting from the experimental technique. Application is made to ICP discharges in noble gases. The measurements are performed in a magnetic multi-pole ICP discharge at a filling gas pressure of 20 Pa. Densities up to $\approx 1 \cdot 10^{14}$ cm^{-3} are obtained and a non-linear dependence on the power is observed for all noble gases. By comparison with an analytical model electron pressure and gas heating effects are identified. Measurements and model show good agreement suggesting that neutral gas depletion due to a very high electron pressure (up to 80% of the filling gas pressure) is the major reason for the observed trends.

10:45
NR1 3 Progresses on resonance hairpin probe SHANTANU KARKARI, *Institute for Plasma Research, Bhat, Gandhinagar* NISHANT SIRSE, GURUSHARAN SINGH GOGNA, MILES TURNER, *Dublin City University, Ireland* This paper briefly reviews the recent developments on resonance hairpin probe as a diagnostic tool for characterizing low temperature electro-negative and strongly magnetized plasmas. As well known the hairpin is capable of measuring absolute values of electron density provided the plasma surrounding the pins is homogeneous and free from adjoining dielectrics. However this is far from reality because of several factors that influence the actual resonance condition such as the proximity of the probes ceramic support and the presence of sheaths around the resonator pins all contributing to the effective permittivity observed by the hairpin. On the other hand dual resonance frequency has been observed in magnetized plasma. The hairpin probe was also applied in conjunction with pulsed laser photo-detachment for measuring time-resolve negative ion density in pulsed-dc magnetron discharge. Recently an independent method based on a pulsed hairpin probe is developed for quantifying electronegative plasma parameters. Using this method both negative ion density and its temperature has been estimated. The results are

found to be in good qualitative agreement with those obtained from pulsed photo-detachment technique.

11:00
NR1 4 ABSTRACT WITHDRAWN

11:15
NR1 5 Diode laser heterodyne interferometry for refractive index measurement of small-scale plasmas in high pressure gases* KEIICHIRO URABE, HITOSHI MUNEOKA, SVEN STAUSS, KAZUO TERASHIMA, *The University of Tokyo* The electron density is one of the most important plasma parameters; however, the behavior of the electron density in high-pressure small-scale plasmas (so-called microplasmas) is still not well understood. We have studied the electron density in direct-current microplasmas operated at atmospheric pressure by using laser heterodyne interferometry and reported some results using CO_2 laser as a light source. By measuring the temporal evolutions of the refractive index of the plasmas by the interferometer, the temporal changes of the electron and gas number densities can be derived. Because of its shorter wavelength, using near-infrared diode laser (890 nm) as a light source allows improving the spatial resolution of the measurement over that obtained using a CO_2 laser (10.6 μm). Furthermore, by replacing a lock-in amplifier used in our previous CO_2-laser interferometry by a custom-made phase detecting module, the response time and temporal resolution of the measurements could be improved. Finally, we discuss potentials of the diode laser interferometry for the measurement of electron and gas number densities with the measurement results of pulsed microplasmas operated in atmospheric and higher pressure gases.

11:30
NR1 6 Cavity Enhanced Thomson Scattering for Low Temperature Plasmas AZER YALIN, ADAM FRISS, BRIAN LEE, ISAIAH FRANKA, *Colorado State University, Fort Collins, CO, 80523, USA* This contribution describes the design, simulation, and initial experimental development of a novel laser Thomson scattering (LTS) system for measurement of weakly-ionized low temperature plasmas. The LTS approach uses a high power intra-cavity beam of power $\sim$10-100 kW to provide increased scattered photon counts and sensitivity as compared to conventional LTS experiments that use light sources with orders of magnitude lower average power. The high power intra-cavity beam is generated by locking a narrow linewidth source laser to a high-finesse optical cavity via

Pound-Drever-Hall locking. The plasma (to be studied) is housed with the high-finesse optical cavity. The high-power source is combined with a detection system comprised of a high-suppression triple monochromator and a low-noise photomultiplier tube used in photon counting mode. We present simulations of signal strengths and scattering spectra including elastic scatter background, detector dark counts, and random (counting) noise contributions. Expected experimental performance is assessed from fits to the simulated data. The number density and electron temperature of a 10^{10} cm^{-3} plasma should be accurately measurable with standard deviation of <5% in a measurement time of 5 minutes per wavelength channel. We also present experimental development including characterization of laser locking, and initial Rayleigh and Raman signals which will be used to calibrate the Thomson system.

11:45
NR1 7 Diagnostics of inductively-coupled plasmas in HBr: Bromine atom and electron densities* JEAN-PAUL BOOTH, NISHANT SIRSE, ROBERT SORIANO, MICKAEL FOUCHER, PASCAL CHABERT, *LPP-CNRS, Ecole Polytechnique* Inductively-coupled plasmas (ICP) containing hydrogen bromide are widely used gas for conductor-etch applications, often using mixtures with Cl_2 and O_2. However, very few scientific studies (whether theoretical, simulation or experimental) have been made of HBr plasmas. We have studied pure HBr plasmas in an industrial-scale ICP (diameter 550 mm, height 100 mm, excited at 13.56 MHz by a 4-turn planar coil) adapted for advanced diagnostic techniques. We have developed a new detection scheme for Br atoms using two-photon laser-induced fluorescence (TALIF). The relative variation of Br atoms was determined as a function of HBr pressure (5-90 mTorr) and RF power (20-500W). The Br density increases with pressure over this range, although the dissociation fraction (Br density divided by the total gas pressure) decreases with pressure. The Br density also increases with RF power up to about 100W, but then progressively saturates. The Br decay rate was measured in the afterglow of a pulsed plasma. The electron density was determined using a microwave hairpin resonator, and was found to peak at 10 mTorr HBr pressure at all RF powers. This behaviour is very similar to that observed in pure Cl_2, although the densities are about a factor 2 lower in HBr.

12:00
NR1 8 Measurement of Time-Dependent Ion Velocity Distribution Function by Laser Induced Fluorescence in a Cylindrical Hall Thruster with Driven Spoke YUAN SHI, AHMED DIALLO, YEVGENY RAITSES, *Princeton Plasma Physics Laboratory* STEPHANE MAZOUFFRE, *ICARE-CNRS* This paper reports, for the first time, effects of spoke on ion velocity distribution function measured by time-resolving laser induced fluorescence. To scan ion speed, the $5d^4F_{5/2}$-$6p^4D_{5/2}$ transition of Xe+ is excited using tunable diode laser. Photons from $6p^4D_{5/2}$-$6s^4P_{3/2}$ transition are collected by a photomultiplier tube and counted by a multichannel scaler. To subtract background, a mechanical chopper is used to generate laser pulses whose power is monitored by a photodiode. To achieve phase-locked accumulation of fluorescence photons, spoke is driven using successively phase-shifted square waves on anode segments and the driving signal is used to synchronize photon accumulation to spoke in data post processing. To resolve three ion velocity components, two laser beams are established, with one beam measuring axial velocity and the other beam measuring some linear combination of radial and azimuthal velocities, depending on the

position of collection volume with respect to thruster plume. Measurements shows ion distribution function oscillates with spoke. Along the thruster axis, ion density is strongly modulated while axial ion velocities are not affected. Off-axis effects of spoke will also be discussed.

Contributed Papers

10:00
NR2 1 Simulating the Spontaneous Formation of Self-Organized Anode Spot Patterns in Arc Discharges JUAN TRELLES, *University of Massachusetts Lowell* Self-organized pattern formation is a captivating phenomenon common in numerous biological, chemical and physical systems. The experimental observation of self-organized anode patterns in diverse types of electrical discharges, including atmospheric-pressure arc discharges, has been well reported and characterized in the plasma literature. Nevertheless, the capturing of anode pattern formation in arc discharges by fluid flow models has proven exceedingly elusive. For the first time computational simulations, based on a time-dependent three-dimensional thermodynamic nonequilibrium model, reveal the spontaneous formation of self-organized anode attachment spots patterns in a free-burning arc. The characteristics of the patterns depend on the total arc current and on the resolution of the spatial discretization, whereas the main properties of the plasma, such as maximum temperatures, velocity, and voltage, depend only on the former. The obtained patterns qualitatively agree with experimental observations and confirm that the spots originate at the fringes of the arc - anode attachment. The results imply that heavy-species - electron energy equilibration, in addition to thermal instability, has a dominant role in the formation of anode spots in arc discharges.

10:15
NR2 2 Effects of Asymmetric Secondary Emission on Plasma Properties of ExB Discharges HONGYUE WANG, *Beihang University; Princeton Plasma Physics Laboratory* MICHAEL CAMPANELL, IGOR KAGANOVICH, ALEXANDER KHRABROV, YEVGENY RAITSES, *Princeton Plasma Physics Laboratory* DMYTRO SYDORENKO, *University of Alberta* GUOBIAO CAI, *Beihang University* In low-pressure devices, the electron mean free path exceeds the size of the system; therefore, the secondary electrons penetrate the bulk plasma and exit to the opposite wall without undergoing collisions. Thus, secondary electron emission (SEE) fluxes affect the charged particle flux balance on walls far from their origination source. As a result, the sheaths at opposite walls are not independent of each other. In this paper, the emission and recollection of electrons by walls is studied using a 1-D model with the asymmetric secondary emission from the inner and outer walls of the ExB device. Plasma properties in a typical ExB discharge channel were simulated using particle-in-cell EDIPIC code. The potential profile becomes significantly asymmetric with decrease of the left SEE yield as compared to the right one. A large proportion of beam electrons moving towards left are reflected by the left sheath. Simulations results for the sheath potential near the right wall show that it is almost constant and is

independent of emission from the left wall. However, change in the SEE at the left wall strongly affects the sheath potential at this wall. The analytic relation between the wall potentials and the SEE yields is derived. SEE asymmetry leads to increase of ion energy loss to the walls due to increase of the sheath potential near the wall with smaller emission.

10:30
NR2 3 Molecular dynamics simulation of plasma-induced Si substrate damage: Latent defect structures and bias-frequency effects* KOJI ERIGUCHI, ASAHIKO MATSUDA, YOSHINORI TAKAO, KOUICHI ONO, *Kyoto University* Plasma-induced physical damage (PPD)—the ion bombardment on Si substrate—has been one of the critical issues for fabricating scaled electronic devices [1], because it degrades the device performance and reliability [2]. The typical damaged structure consists of a surface layer and latent defect sites underneath the surface. To minimize PPD, various techniques that control an ion energy distribution function (IEDF) have been developed [3]. In this study, a classical molecular dynamics (MD) simulations [4] were performed in various gas systems (Ar, Xe, Cl, Br etc.) to clarify the latent defect structure and the effects of IEDF on PPD, where incident ion energies were defined to obey a given IEDF—substrate bias frequency. We revealed that both the density of defect site and the damaged-layer thickness were weak functions of IEDF, which are consistent with a binary-collision-based range model and experimental results [5].

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[4] H. Ohta and S. Hamaguchi, J. Vac. Sci. Technol. **A19**, 2373 (2001).
[5] K. Eriguchi *et al.*, Jpn. J. Appl. Phys. **49**, 056203 (2010).

10:45
NR2 4 Secondary electron emission yield dependence on the Fermi level in Silicon* DAVID URRABAZO, MATTHEW GOECKNER, LAWRENCE OVERZET, *University of Texas at Dallas* Secondary Electron Emission (SEE) by ion bombardment plays a key role in determining the properties of many plasmas. As a result, significant efforts have been expended to control the SEE coefficient (increasing or decreasing it) by tailoring the electron work function of surfaces. A few recent publications point to the possibility of controlling the SEE coefficient of semiconductor surfaces in real time through controlling the numbers of electrons in the conduction band near the surface. Large control over the plasma was achieved by injecting electrons into the semiconductor just under the cathode surface via a subsurface PN junction. The hypothesis was that SEE is dependent on the numbers of electrons in the conduction band near the surface (which is related to the position of the Fermi level near the surface). We are testing the validity of this hypothesis. We have begun fundamental ion beam studies to explore this possible dependence of SEE on the Fermi energy level using Si. Various doping levels and dopants are being evaluated and the results of these tests will be presented.

11:00
NR2 5 Experimental Evidence of Change in Sheath Properties due to Secondary Electron Emission in a Crossed Field Plasma Setup* KAPIL SAWLANI, JOHN FOSTER, *University of Michigan, Ann Arbor, MI 48109* The nature of plasma transport across the magnetic field in crossed-field (CF) devices remains largely an unsolved problem. This can be further complicated by the presence of secondary electrons derived from electron impact on walls. The coupling of these electrons to the bulk plasma and their role in CF plasma transport is also not well understood. The emission of secondary electrons from wall surfaces also affects the sheath potential, thus impacting energy transport to the wall. In this work, a benchtop apparatus is used to elucidate the role that secondary electrons play in regards to CF transport and energy flow to the walls. An electron beam is used to generate a secondary electron plume at the surface of an insulating target. The CF device plasma response to these secondary electrons is assessed by measuring changes to the potential distribution in the sheath of the irradiated target and the measured electron energy distribution function. The variation in the discharge voltage at fixed emission current is also determined which yields insight into CF impedance. The effect of the variation of the electron beam's angle of incidence on the CF current is also characterized. An attempt is made to relate phenomena and trends observed in this work with those in Hall thrusters.

11:15
NR2 6 Combined plasma and molecular dynamics simulations for a better prediction of plasma surface interactions: Cryogenic etching of silicon with fluorine-containing gases STEFAN TINCK, ERIK NEYTS, ANNEMIE BOGAERTS, *University of Antwerp* PLASMANT TEAM A hybrid Monte Carlo-fluid plasma model as well as molecular dynamics (MD) simulations are applied together to obtain detailed information on surface reaction mechanisms during plasma processing. With this modeling setup, results on the surface behavior of fluorine plasma species etching Si wafers at room and cryogenic temperatures will be discussed. When numerically investigating low pressure plasmas used for microelectronics applications, one should always consider wall effects if possible. Especially in low pressure plasmas, where collisions with the reactor walls and wafer are quite probable compared to gas phase collisions, knowing at which rate the plasma species are lost or produced at these surfaces is of utmost importance. Unfortunately, the probabilities of wall reactions such as sticking, reflection, incorporation, etching or sputtering are often not well known. With MD, these surface reaction probabilities can be calculated and applied as input in the plasma simulation. In this modeling setup, surface probabilities as a function of surface temperature, chemical composition and reactor operating conditions are obtained and considered for the overall plasma simulation for a better description of the investigated plasma process.

11:30
NR2 7 Reversible plasma-based functionalization of advanced carbon materials EVA KOVACEVIC, JOHANNES BERNDT, *GREMI, University of Orleans* THOMAS STRUNSKUS, *Christian-Albrechts-University of Kiel, Germany* NICOLAS CAMARA, *GREMAN, Tours, France* CHRISTOPHE CACHONCINLLE, MIREILLE GAILLARD, CHANTAL BOULMER-LEBORGNE, *GREMI, University of Orleans, France* Advanced carbon materials, such as graphene, carbon nanotubes or nanoparticles possess unique chemical and physical properties that make them interesting for wide area of applications, ranging from their use in electronics, as fillers for novel composite materials or as base for the development of new chemical sensors and catalysts.

The key challenge to be overcome for actual applications is the simple and stable tuning of the surface properties of these materials. This contribution deals with the capacitively coupled discharges that are a versatile tool for the synthesis of such materials and at the same time also suitable for their surface modifications. We focus here on our results concerning the production and controlled and reversible covalent functionalization of advanced carbon materials. The quality of the deposits and the effect of the plasma treatments are analyzed by means of transmission electron microscopy, near edge X-ray absorption fine structure spectroscopy (NEXAFS), high resolution X-ray Photoelectron Spectroscopy (XPS), and contact angle measurements. Special attention is paid to the reversibility of the plasma induced functionalization by use of plasma based EUV photon irradiation.

11:45

NR2 8 Optimization of plasma ionization sources for ambient mass spectrometry surface analysis KIRSTY MCKAY, JUN-SEOK OH, ANDREW BOWFIELD, *University of Liverpool* TARA SALTER, *National Physical Laboratory* JAMES WALSH, *University of Liverpool* IAN GILMORE, *National Physical Laboratory* JAMES BRADLEY, *University of Liverpool* The use of low-temperature atmospheric pressure plasma sources in ambient surface analysis mass spectrometry has received growing interest in recent years. Due to their unique chemical and electrical properties plasmas provide a gentle and efficient means of ionizing surface compounds in their natural environment, with little to no sample preparation required. In this study we investigate how these plasma ionization sources might be optimized for ambient surface analysis techniques. An ambient molecular beam mass spectrometer from Hiden Analytical Ltd. (HPR-60) is used to monitor the charged ion species emanating from two different plasma sources, a pulse modulated RF (13.56 MHz) plasma needle and a continuous wave kHz plasma jet, under different operating parameters. Both time-averaged and time-resolved ion intensity measurements reveal the species present in the discharges and the underlying production and loss mechanisms for different operating conditions. To assess the effectiveness of each of these plasmas sources as tools for surface ionization/desorption, a number of different pharmaceutical and polymer surfaces were analyzed in both positive and negative ion mode using a hybrid linear trap quadrupole (LTQ) orbitrap mass spectrometer, due to its increased mass sensitivity.

12:00

NR2 9 Plasma-Surface Interactions and Feature Profile Simulations PAUL MOROZ, *Tokyo Electron US Holdings, Inc.* DANIEL MOROZ, *University of Pennsylvania* Plasma-surface interactions are rather complex in most cases. One has to take into account not only sticking of gaseous species from plasma to the surface of solid materials or a set of chemical reactions on the surface producing solid and gaseous products, but also interactions of atoms within deeper layers of the material. Etching, deposition, and implantation processes usually go on at the same time. Energetic particles, such as ions or fast neutrals, could penetrate and etch materials even in conditions when significant polymer layers are present. Here, we present a 2D and 3D feature profile simulator FPS3D which is based on the cellular model and takes into account finite penetration depths of energetic particles. It can also do simulations for very delicate conditions, such as ALD, when materials are deposited only by a single atomic layer at a time. Using cells each containing a single molecule could introduce significant errors into calculations as sizes of molecules could differ significantly, and thus we are using a different approach trying to mimic MD simulations with various approximations and on a larger scale. The code is applicable to nanometer through micrometer range of features, at least, and it is fast both for 2D and 3D simulations.

SESSION NR3: PLASMA BOUNDARIES: SHEATHS, BOUNDARY LAYERS, OTHERS
Thursday Morning, 3 October 2013; Room: Nassau Room at 10:00; Greg Severn, University of San Diego, presiding

Invited Papers

10:00
NR3 1 Experimental validation of sheath models at intermediate radio frequencies
MARK SOBOLEWSKI, *National Institute of Standards and Technology*

Sheaths in radio-frequency (rf) discharges play a dominant role in determining important properties such as the efficiency of power delivery and utilization, plasma spatial uniformity, and ion energy distributions (IEDs). To obtain high quality predictions for these properties requires sheath models that have been rigorously tested and validated. We have performed such tests in capacitively coupled and rf-biased inductively coupled discharges, for inert as well as reactive gases, over two or more orders of magnitude in frequency, voltage, and plasma density. We measured a complete set of model input and output parameters including rf current and voltage waveforms, rf plasma potential measured by a capacitive probe, electron temperature and ion saturation current measured by Langmuir probe and other techniques, and IEDs measured by mass spectrometers and gridded energy analyzers. Experiments concentrated on the complicated, intermediate-frequency regime of ion dynamics, where the ion transit time is comparable to the rf period and the ion current oscillates strongly during the rf cycle. The first models tested used several simplifying assumptions including fluid treatment of ions, neglect of electron inertia, and the oscillating step approximation for the electron profile. These models were nevertheless able to yield rather accurate predictions for current waveforms, sheath impedance, and the peak energies in IEDs. More recently, the oscillating step has been replaced by an exact solution of Poisson's equation. This results in a modest improvement in the agreement with measured electrical characteristics and IED peak amplitudes. The new model also eliminates the need for arbitrary or nonphysical boundary conditions that arises in step models, replacing them with boundary conditions that can be obtained directly from measurements or theories of the presheath.

Contributed Papers

10:30
NR3 2 An algebraic RF sheath model for all excitation waveforms and amplitudes, and all levels of collisionality* RALF PETER BRINKMANN, ABD ELFATTAH ELGENDY, HOMAYOUN HATEFINIA, MOHAMMED SHIHAB, TORBEN HEMKE, ALEXANDER WOLLBY, DENIS EREMIN, THOMAS MUSSENBROCK, *Theoretical Electrical Engineering, Ruhr-University Bochum* The boundary sheath of a low temperature plasma comprises typically only a small fraction of its volume but is responsible for many aspects of the macroscopic behavior. A thorough understanding of the sheath dynamics is therefore of theoretical and practical importance. This work focusses on the so-called "algebraic" approach which strives to describe the electrical behavior of RF modulated boundary sheaths in closed analytical form, i.e., without the need to solve differential equations. A mathematically simple, analytical expression for the charge-voltage relation of a sheath is presented which holds for all excitation wave forms and amplitudes and covers all regimes from the collision-less motion at low gas pressure to the collision dominated motion at gas high pressure. A comparison with the results of self-consistent particle-in-cell simulations is also presented.

*Deutsche Forschungsgemeinschaft DFG via SFB TR 87.

10:45
NR3 3 Student Award Finalist - Instability and Inversion of the Sheath Potential Caused by Electron Emission* MICHAEL CAMPANELL, *Princeton Plasma Physics Laboratory* HONGYUE WANG, *Beihang University* ALEX KHRABROV, IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory* Most theories of PSI with electron emission assume a temporally stable sheath exists and the plasma potential is positive relative to the wall [1]. Ions are assumed to be drawn to the wall via Bohm's criterion and the emission is treated as a fixed "coefficient." We show if the emission is sufficiently strong, the presheath may disappear because there is no need for ions to reach the wall to maintain current balance or plasma shielding. In this "inverse sheath" regime, the wall charge is positive and the shielding charge is negative. The plasma potential is negative, ions are confined and plasma electrons are unconfined [2]. We also present simulations and theory on a class of sheath instabilities driven by secondary emission that can arise under general conditions [3,4]. Lastly, we analyze effects of emitted electrons transiting between surfaces in bounded plasmas; transit alters flux balance [5] compared to PSI models of one emitting wall [1].

*This work was supported by the U.S. Department of Energy and the U.S. Air Force Office of Scientific Research.

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[3]M.D. Campanell *et al.*, PRL **108**, 235001 (2012).
[4]M.D. Campanell *et al.*, POP **19**, 123513 (2012).
[5]M.D. Campanell and H. Wang, submitted to APL (2013).

11:00
NR3 4 The Langmuir's Paradox: Can the Ion Acoustic Instability at the Sheath Edge Thermalize the Ions Too?* CHI-SHUNG YIP, NOAH HERSHKOWITZ, *University of Wisconsin - Madison Madison, WI, USA* GREG SEVERN, *University of San Diego, San Diego, CA, USA* Recently a theoretical prediction was that in single-species plasmas, ion-ion collisional friction is enhanced by the ion acoustic instability [1]. The theory predicted that the instability will not only enhance the thermalization of the electrons, but will also, near the sheath-edge, thermalize the non-Maxwellian tail of the ion velocity distribution function (IVDF), caused by charge exchange in the presheath. The theory also predicted that this instability disappears through collisional damping as neutral pressure of the plasma increases. This experiment aims to verify this theory by measuring the IVDFs near the sheath edge in a multi-dipole chamber discharge in Argon and Xenon gas for a variety of neutral pressures and electron temperatures. The threshold parameters of the phenomenon are explored. The IVDFs are determined by Laser-Induced Florescence, the electron temperature is measured by a Langmuir probe and the plasma potential towards the boundary is measured by an emissive probe.

*DOE Grant nos. DE-SC0001939, DE FG02- 03ER54728, and NSF No. CBET0903832.

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11:15
NR3 5 End-boundary sheath potential, Langmuir waves, electron and ion energy distribution in the low pressure DC powered Non-ambipolar Electron Plasma LEE CHEN, ZHIYING CHEN, MERRITT FUNK, *Tokyo Electron America, Inc., Austin, TX 78741* The non-ambipolar electron plasma (NEP) is heated by electron beam extracted from the electron-source Ar plasma through a dielectric injector by an accelerator located inside NEP. NEP pressure is in the 1-3mTorr range of N_2 and its accelerator voltage varied from $V_A = +80$ to $V_A = +600V$. The non-ambipolar beam-current injected into NEP is in the range of 10s Acm^{-2} and it heats NEP through beam-plasma instabilities. Its EED f has a Maxwellian bulk followed by a broad energy-continuum connecting to the most energetic group with energies above the beam-energy. The remnant of the injected electron-beam power terminates at the NEP end-boundary floating-surface setting up sheath potentials from $V_S = 80$ to $V_S = 580V$ in response to the applied values of V_A. The floating-surface is bombarded by a space-charge neutral plasma-beam whose IED f is near mono-energetic. When the injected electron-beam power is adequately damped by NEP, its end-boundary floating-surface V_S can be linearly controlled at almost 1:1 ratio by V_A. NEP does not have an electron-free sheath; its "sheath" is a widen presheath that consists of a thermal presheath followed by an "anisotropic" presheath, leading up to the end-boundary floating-surface. Its ion-current of the plasma-beam is much higher than what a conventional thermal presheath can supply. If the NEP parameters cannot damp the electron beam power sufficiently, V_S will collapse and becomes irresponsive to V_A.

Invited Papers

11:30
NR3 6 Particle-in-cell simulations of discharges with intense electron emission* DMYTRO SYDORENKO, *University of Alberta, Edmonton, Alberta, Canada*

In many plasma devices, the plasma is bounded by walls which emit electrons due to secondary electron emission or thermionic emission. At low pressures, the electron mean free path exceeds the plasma dimensions, and the emitted electrons accelerated by the intense electric field of the near-wall sheath propagate through the plasma as an electron beam. The beam dynamics in a finite length system is different from theoretical predictions for infinite or periodic plasmas. This presentation gives a summary of numerical studies of beam-plasma interaction in Hall thrusters and dc discharges carried out with a particle-in-cell code [1]. The code resolves one spatial coordinate and three velocity components, it is based on the direct implicit algorithm [2], the electron-to-ion mass ratio is realistic, numerous collisions between electrons and neutrals and the Coulomb collisions are included, code performance is enhanced with the help of MPI parallelization. The following effects are discussed: vanishing of the two-stream instability due to modification of the bulk electron velocity distribution [3], sheath instability in Hall thrusters [4], intermittency and multiple regimes of the two-stream instability in dc discharges.

[1] D. Sydorenko *et al.*, Phys. Plasmas **13**, 014501 (2006).
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[4] D. Sydorenko *et al.*, Phys. Plasmas **15**, 053506 (2008).

SESSION PR1: HIGH PRESSURE DISCHARGES: DIELECTRIC BARRIER DISCHARGES, CORONAS, BREAKDOWN, SPARKS III
Thursday Afternoon, 3 October 2013; Room: Ballroom I at 13:30; David Scott, George Washington University, presiding

Invited Papers

13:30
PR1 1 Meter-Scale Atmospheric-Pressure Microwave Plasma Using Sub-Millimeter-Gap Slot*
HIROTAKA TOYODA, *Nagoya University*

Atmospheric-pressure pulsed plasmas have been given much attention because of its various possibilities for industrial applications such as surface wettability control, sterilization and so on. Among various atmospheric-pressure plasma sources, microwave plasma that is produced inside waveguide-slots is attractive because high-density plasma up to 10^{15} cm^{-3} can be easily produced along very long waveguide with light-weight and rather simple antenna configuration. So far, we have investigated plasma production inside slot of the waveguide and in this talk, elongation of the plasma up to meter-scale with newly-designed plasma source will be presented. In this study, two types of antennas are proposed to elongate the atmospheric-pressure microwave plasma. Firstly, array-structured slot design with a closed-end waveguide is adopted using X-band microwave (10 GHz). In this structure, slot antennas with a total number of more than 40 are positioned with $\lambda_g/2$-pitch along $\sim$1m waveguide so as to utilize standing wave inside the waveguide and to increase the electric field inside the slot. By optimizing the antenna design, arrayed microwave plasmas are successfully produced along $\sim$1m-length waveguide. The arrayed-slot structure, however, the plasma is not completely uniform along the waveguide and plasma density drastically decreases between two adjacent slots. To solve this, an alternative type of antenna that is free from the standing wave effect is designed. In this new-type antenna, travelling wave inside the waveguide with no reflection wave is realized by a combination of a microwave circulator and a ring-structured waveguide. By this transmission line, microwave power flows only to one direction and the average microwave power becomes spatially uniform along the waveguide. By using a single but very long slot up to several tens cm, very uniform plasma is produced along the slot. The result strongly suggests easy scale-up of the plasma source more than one meter that can be applied to surface modification of large-scale devices.

Contributed Papers

14:00
PR1 2 Enhanced ozone production in a pulsed dielectric barrier discharge plasma jet with addition of argon to a He-O$_2$ flow gas BRIAN SANDS, *UES, Inc.* BISWA GANGULY, JAMES SCOFIELD, *Air Force Research Laboratory* Ozone production in a plasma jet DBD driven with a 20-ns risetime unipolar pulsed voltage can be significantly enhanced using helium as the primary flow gas with an O$_2$ coflow. The overvolted discharge can be sustained with up to a 5% O$_2$ coflow at <20 kHz pulse repetition frequency at 13 kV applied voltage. Ozone production scales with the pulse repetition frequency up to a "turnover frequency" that depends on the O$_2$ concentration, total gas flow rate, and applied voltage. For example, peak ozone densities $>10^{16}$ cm^{-3} were measured with 3% O$_2$ admixture and <3 W input power at a 12 kHz turnover frequency. A further increase in the repetition frequency results in increased discharge current and 777 nm O(^5P) emission, but decreased ozone production and is followed by a transition to a filamentary discharge mode. The addition of argon at concentrations $\geqslant$5% reduces the channel conductivity and shifts the turnover frequency to higher frequencies. This results in increased ozone production for a given applied voltage and gas flow rate. Time-resolved Ar($1s_5$) and He(2^3S_1) metastable densities were acquired along with discharge current and ozone density measurements to gain insight into the mechanisms of optimum ozone production.

14:15

PR1 3 Streamer dynamics scaling with positive polarity pulsed voltage and gas pressure in a helium plasma jet ROBERT LEIWEKE, *UES, Inc* BISWA GANGULY, *Air Force Research Laboratory* We have investigated the variation of streamer speed, current, diameter and emission intensity profiles as functions of positive polarity 20 ns rise time pulsed applied voltage ranging from 6 kV up to 11 kV, at 500 Torr gas pressure using a 2 mm diameter helium plasma jet entrained by N_2 co-flow in a 30 mm diameter pyrex cell. The streamer speed has been measured from the spatio-temporal intensity of He $3^3D \to 2^3P$ transition at 589 nm using both PMT and 5 ns gated ICCD imaging; the streamer diameter is obtained from the ICCD imaging. The streamer current was measured using wideband width current sensor and it varied from 0.1 mA up to 0.8 mA. Streamer speed increased almost linearly and peak currents varied nonlinearly with the applied voltage. The streamer diameter, estimated from imaging, was nearly constant at 0.9 mm indicating that the observed streamer may be several overlapping streamers propagating through the helium gas channel. The peak electron density of $\approx 2 \times 10^{10}$ cm^{-3} is estimated from current continuity and streamer diameter. We have also performed voltage dependent streamer dynamics measurements at gas pressures from 150 up to 740 Torr, and the data shows that streamer properties do not follow the same scaling behavior as in air plasma.

14:30

PR1 4 Further Investigations of Slow Lightning KARL STEPHAN, GIL SHELEG, *Ingram School of Engineering, Texas State University, San Marcos, TX 78666 USA* The phenomenon of "slow lightning" is a new type of tracking or sliding atmospheric-pressure resistive-barrier discharge on the surface of a weakly conducting electrolyte. It occurs during the production of water plasmoids (also called "Gatchina discharges") in which a high-voltage capacitor is discharged into an insulated cathode in limited surface contact with the electrolyte. Unlike conventional dielectric-barrier and most other resistive-barrier discharges, these novel discharges propagate on the surface relatively slowly, spreading at a speed of 1-10 meters per second. We have investigated this phenomenon in several ways, using high-speed videography, time- and space-resolved spectroscopy, and current-density profiling. The plasma produced at cathode spots forms the plasmoid, and this plasma is distinct from the plasma in the slow-lightning discharge above the electrolyte. The primary visible emission from the latter discharge is a continuum, probably due to free-bound transitions, although an N2+ band is also present as well as intense emission from OH radicals under certain conditions. Possible applications of this phenomenon include water purification and pollution control.

14:45

PR1 5 Student Award Finalist - Simulation of the reignition of atmospheric pressure air discharges behind dielectric obstacles: comparison with experiments* FRANCOIS PECHEREAU, ANNE BOURDON, *Laboratory EM2C, Ecole Centrale Paris, France* In recent years, experimental studies on plasma assisted catalysis for flue gas treatment have shown a significant reduction of pollutants at a low energetic cost. Catalyst supports are either random or organized two phase media such as pellets, monoliths or porous media. Then, in plasma reactors, atmospheric pressure discharges have to interact with many obstacles and to propagate in microcavities and pores. To better understand the discharge dynamics in these complex structures, experiments have been carried out at LPGP (Orsay, France) in a point-to-plane geometry with a dielectric plane obstacle placed in the discharge path. In this work, we have carried out discharge simulations in the experimental ge-

ometry. We have compared the dynamics of the discharge ignited at the point and its impact on the dielectric surface. Then, we have compared the conditions of a discharge reignition behind the dielectric obstacle. A good qualitative agreement with experiments has been obtained but to improve the quantitative comparison, we have carried out a detailed parametric numerical study. In this work, we will focus on the influence of the level of seed charges on the discharge reignition and discuss several physical processes that could have an impact on the level of seed charges.

SESSION PR2: CAPACITIVELY COUPLED PLASMAS I
Thursday Afternoon, 3 October 2013
Room: Ballroom II at 13:30
Kallol Bera, Applied Materials Inc., presiding

Contributed Papers

13:30

PR2 1 IEDF Skew Control Using Phase Locked Dual Frequency RF Drive HAMILTON CLARK, THERESA KUMMERER, *NC State University* DAVID COUMOU, *MKS Instruments* STEVEN SHANNON, *NC State University* The distribution of ion energies incident on plasma facing surfaces can have a significant impact on process characteristics. Non-sinusoidal [1] and multi-frequency [2] bias drives have demonstrated both the control of IEDF shape and process enhancement brought about by this level of control. In this work, we will present an extension of multi-frequency drive for IEDF control where multiple frequencies that differ by integer multiples are used to drive an RF sheath for ion energy control. By varying the relative voltages and the phase between these independent drives, the distribution skew can be controlled such that the traditional two peak distribution obtained from an RF sheath can be weighted to the low energy peak or the high energy peak with a reasonable level of control. An analytical sheath model is presented to explain this phenomena; experimental measurement of IEDF's using a gridded energy analyzer are also presented, further demonstrating this configuration's ability to control IEDF shape and validating the analytical model used to introduce these concepts.

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[2]Shannon, Hoffman, Yang, Patterson, Holland; JAP **97**, 103304 (2005).

13:45

PR2 2 Evaluation of Equivalent Circuit Models for Plasma Bulk Characterization by Comparing IEDF Predictions with those of a Spatially Resolved CCP Model* SCHABNAM NAGGARY, MOHAMMED SHIHAB, FRANK ATTELN, *Ruhr University Bochum* MUSTAFA MEGAHED, *ESI Group* RALF PETER BRINKMANN, *Ruhr University Bochum* Capacitively coupled radio frequency discharges are widely used in the semiconductor processing industry for thin film deposition and etching. Thus the evaluation of the ion energy distribution function (IEDF) is of paramount importance for industrial applications. Spatially and temporally resolved CCP models are generally computationally expensive leading to reduced applicability of these models for industrial optimization. In order to reduce the simulation time, as an alternative method, we use equivalent circuits based on a global model to characterize the plasma bulk and provide the needed input parameters for a hybrid sheath model [1, 2, 3]. The overall computational time to obtain time averaged IEDFs lies within seconds, hence the concept is very attractive for industrial scanning and optimization. In order to assess the applicability of this

novel approach the results are compared with those of commercial multi-physics software CFD-ACE+ in 2 and 3 dimensions. Our investigation demonstrates the feasibility of the compromise between short simulation times and accurate calculation of spatially resolved IEDF.

[1]M Kratzer *J. Appl. Phys.* **90** (2001).
[2]M Shihab *J. Phys. D: Appl. Phys.* **45** (2012).
[3]A E Elgendy arXiv:1306.1664v1 (2013).

14:00
PR2 3 A particle-in-cell/Monte Carlo simulation of a capacitively coupled chlorine discharge JON T. GUDMUNDSSON, *University of Iceland* SHUO HUANG, *University of Michigan - Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University* We demonstrate the oopd1 (object oriented plasma device for one dimension) particle-in-cell/Monte Carlo simulation tool for the capacitively coupled chlorine discharge with a comprehensive reaction set. The simulation results are compared with available experimental measurements and good agreement is achieved. We explore a typical capacitively coupled chlorine discharge operated at both single frequency and dual frequency using oopd1 and obtain key plasma parameters, including particle density, effective electron temperature, electron energy probability function and ion energy and angular distributions for both Cl^+ and Cl_2^+ ions. The dependence of the plasma parameters on the discharge pressure is systematically investigated. As the pressure increases from 5 mTorr to 100 mTorr, the heating mechanism evolves from both stochastic and ohmic heating to predominantly ohmic heating and the electron heating outweighs the ion heating at high pressure. The creation of Cl^+ ions in the sheath region is mainly due to conversion from Cl_2^+ ions to Cl^+ ions through non-resonant charge exchange, while in the bulk region the creation of Cl+ ions is mainly ascribed to electron impact ionization processes.

14:15
PR2 4 Numerical Confirmation of the Feasibility to Generate Uniform Large-Area VHF Plasmas by Launching a Travelling Wave HSIN-LIANG CHEN, YEN-CHENG TU, CHENG-CHANG HSIEH, WEN-FA TSAI, CHI-FONG AI, *Physics Division, Institute of Nuclear Energy Research (INER)* KEH-CHYANG LEOU, *Department of Engineering and System Science, National Tsing Hua University* Large-area VHF (very high frequency) PECVD has been demonstrated to be an effective approach to improve the throughput of thin film silicon solar cell industry because it could increase the deposition rate without deteriorating the film quality. An innovative approach, i.e., creating a traveling wave in the discharge region by simultaneously launching two specific standing waves, is proposed to generate uniform large area VHF plasmas. The feasibility of this approach has been successfully verified by numerical simulation in this study. The spatial distribution of electric field for each standing wave is separately controlled by the phase difference (φ) between the corresponding two feeding points placed on opposite sides of electrode and designated to produce a specific standing wave pattern. The simulation results indicate that the standing wave patterns obtained with φ equal to 0° and 180° waves are spatially out of phase by 90° and the corresponding standing patterns are consistent with various experimental works. By launching these two standing waves at the same time, a traveling wave can be generated once the conditions that these two standing waves must possess the same amplitude and be 90° out of phase in terms of time are also fulfilled. To provide useful information

for diagnostics, how the deviations from the necessary conditions would affect discharge patterns are discussed in details.

14:30
PR2 5 Higher harmonic waves and a center-peaked plasma density profile in VHF-CCP reactors IKUO SAWADA, *Tokyo Electron US Holdings Inc.* BARTON LANE, PETER VENTZEK, *Tokyo Electron America* ROCHAN UPADHAY, *Esgee Technologies Inc.* LAXMINARAYAN RAJA, *University of Texas at Austin* Measurements of electron density profile and higher harmonic waves were performed in a very high frequency parallel-plate capacitively coupled plasma test-bench reactor. An Argon plasma was generated with a single frequency feed from the upper electrode at pressures of 20 to 100 mTorr. The driving frequencies were 60 or 100 MHz with electron densities ranging from 2e16 to 2e17[1/m3]. With increasing power, a center peak in the density profile becomes prominent. At higher densities, over 5e16[1/m3], a very sharp and localized center-peaked density profile is observed. On the contrary, a broad center peak is observed at lower densities. In order to elucidate the mechanism leading to center-peaked profiles, both experimental measurement and numerical calculation of higher harmonic spectrum were performed. A relationship between higher harmonics waves over 400 MHz and a very sharp center-peaked density profile was found and is described.

14:45
PR2 6 Observation of an abrupt electron heating mode transition in capacitive single radio frequency discharges* SEBASTIAN WILCZEK, JAN TRIESCHMANN, JULIAN SCHULZE, RALF PETER BRINKMANN, THOMAS MUSSENBROCK, *Ruhr University Bochum* ARANKA DERZSI, IHOR KOROLOV, ZOLTAN DONKÓ, *Wigner Research Center for Physics, Budapest* The electron heating in capacitive discharges at very low pressures ($\approx$1 Pa) is dominated by stochastic heating. In this regime electrons are accelerated by the oscillating sheaths, traverse through the plasma bulk and interact with the opposite sheath. By varying the driving frequency or the gap size of the discharge, energetic electrons reach the sheath edge at different temporal phases, i.e., the collapsing or expanding phase, or the moment of minimum sheath width. This work reports numerical experiments based on Particle-In-Cell simulations which show that at certain frequencies the discharge switches abruptly from a low density mode in a high density mode. The inverse transition is also abrupt, but shows a significant hysteresis. This behavior is explained by the complex interaction of the bulk and the sheath.

SESSION PR3: GAS PHASE PLASMA CHEMISTRY
Thursday Afternoon, 3 October 2013
Room: Nassau Room at 13:30
Timo Gans, University of York, presiding

Contributed Papers

13:30
PR3 1 Reaction kinetics of a kHz-driven atmospheric pressure plasma with humid air impurities* T. MURAKAMI, *Tokyo Institute of Technology* Q. TH. ALGWARI, *University of Mosul* K. NIEMI, T. GANS, D. O'CONNELL, *University of York* W.G. GRAHAM, *Queen's University Belfast* Atmospheric-pressure plasma jets (APPJs) have been gaining attention because of their great

potential in bio-plasma applications. It is important to know the complex chemical kinetics of the reactive multi-species plasma. This is a study starting to address this by using a 0D time-dependent global simulation (comprising 1050 elementary reactions among 59 specie [1]) of kHz-driven (20 kHz) APPJ with a helium-based oxygen-mixture (0.5%) with ambient humid air impurity. The present model is initiated from time dependent measurements and estimates of the basic plasma properties [2]. The dominant neutral reactive species are reactive oxygen species and atomic hydrogen. The positive and negative oxygen ions and electrons are the most pronounced charged species. While most of the neutral reactive species are only weakly modulated at the driving frequency, the atomic oxygen metastables and atomic nitrogen metastables are strongly modulated. So are also the electrons and most of the positive and negative ions, but some are not, as will be discussed.

[1] T. Murakami et al., Plasma Sources Sci. Technol. 22 (2013) 015003.
[2] Q. Th. Algwari and D. O'Connell, Appl. Phys. Lett. 99 (2011) 121501.

13:45
PR3 2 Homogeneous and Heterogeneous Reaction Mechanisms in CH_3F-O_2 Inductively Coupled Plasmas* VINCENT M. DONNELLY, ERDINC KARAKAS, SANBIR KALER, QIAOWEI LOU, DEMETRE J. ECONOMOU, *University of Houston* CH_3F/O_2 containing plasmas are used in selective Si_3N_4 etching over Si or SiO_2. Fundamental plasma studies in these gas mixtures are scarce. In this work, optical emission rare gas actinometry and a global chemistry model were employed to study inductively couple plasmas in CH_3F/O_2 gas mixtures. For constant CH_3F and O_2 flow rates, the absolute H, F and O atom densities increased linearly with power. The feedstock gas was highly dissociated and most of the fluorine and oxygen was contained in reaction products HF, CO, CO_2, H_2O and OH. Measured number densities as a function of O_2 addition to CH_3F/O_2 changed abruptly for H, O, and particularly F atoms (factor of 4) at 48% O_2 A corresponding transition was also observed in electron density, electron temperature and gas temperature, as well as in C, CF and CH optical emission. These abrupt transitions were attributed to the reactor wall reactivity, changing from a polymer-coated surface to a polymer-free surface, and vice-versa, as the O_2 content in the feed gas crossed 48%. Homogeneous chemistry dominates above 48% O_2; a kinetic model with no adjustable parameters is in excellent agreement with the absolute F and H and relative HF number density dependence on power and pressure.

14:00
PR3 3 Plasma-assisted combustion in lean, high-pressure, preheated air-methane mixtures* TIMOTHY SOMMERER, JOHN HERBON, SEYED SADDOUGHI, *General Electric Research* MAXIM DEMINSKY, BORIS POTAPKIN, *Kintech Lab Ltd* We combine a simplified physical model with a detailed plasma-chemical reaction mechanism to analyze the use of plasmas to improve flame stability in a gas turbine used for electric power generation. For this application the combustion occurs in a lean mixture of air and methane at high pressure (18.6 atm) and at "preheat" temperature 700 K, and the flame zone is both recirculating and turbulent. The system is modeled as a sequence of reactors: a pulsed uniform plasma (Boltzmann), an afterglow region (plug-flow), a flame region (perfectly-stirred), and a downstream region (plug-flow). The plasma-chemical reaction mechanism includes electron-impact on the feedstock species, relaxation in the afterglow to neutral molecules and radicals, and methane combustion chemistry (GRI-Mech 3.0), with extensions to properly describe low-temperature combustion 700–1000 K [M Deminsky et al., Chem Phys **32**, 1 (2013)]. We find that plasma treatment of the incoming air-fuel mixture can improve the stability of lean flames, expressed as a reduction in the adiabatic flame temperature at lean blow-out, but that the plasma also generates oxides of nitrogen at the preheat temperature through the reactions $e+ N_2 \rightarrow N + N$ and $N + O_2 \rightarrow NO + O$. We find that flame stability is improved with less undesirable NOx formation when the plasma reduced-electric-field E/N is smaller.

14:15
PR3 4 NO Formation and Consumption Mechanisms in a Plasma Filament DAVID BURNETTE, IVAN SHKURENKOV, IGOR ADAMOVICH, WALTER LEMPERT, *The Ohio State University* CHASZEYKA NON-EQUILIBRIUM THERMODYNAMICS LABORATORY TEAM Laser-induced fluorescence measurements have been performed on nitric oxide, oxygen atoms, and nitrogen atoms in low temperature, diffuse plasma filaments of air and air/fuel mixtures. The results have been compared to a one-dimensional numerical model and show that NO is rapidly formed in air as a result of excited species within the plasma and is consumed quickly by the reverse Zel'dovich mechanism. The evolution of the nitric oxide concentration in hydrogen and ethylene fuels is presented and the possibility of additional NO formation channels is discussed.

14:30
PR3 5 A spectroscopic study of ethylene destruction and by-product generation using a three-stage atmospheric packed-bed plasma reactor MARKO HUEBNER,* OLIVIER GUAITELLA,† ANTOINE ROUSSEAU,‡ JUERGEN ROEPCKE,§ *None* Using a three-stage dielectric packed-bed plasma reactor at p = 1 bar the destruction of C_2H_4 and the generation of major by-products have been studied by FTIR spectroscopy. As test gas mixture air containing 0.12% humidity with 0.1% ethylene admixture was used. In addition to the fragmentation of the precursor gas, the evolution of the concentration of ten stable reaction products, CO, CO_2 O_3, NO_2, N_2O, HCN, H_2O, HNO_3, CH_2O and CH_2O_2 has been monitored. Applying three sequentially working discharge cells (f = 4 kHz, U = 9 − 12 kV) a nearly complete decomposition of C_2H_4 could be achieved. In maximum the specific energy deposition was about 900 Jl^{-1}. The value of the specific energy β, characterizing the energy efficiency of the ethylene destruction in the used reactor, was 330 Jl^{-1}. The carbon balance of the plasma chemical conversion of ethylene has been analyzed. As a main result of the study, the application of three reactor stages suppresses essentially the production of harmful by-products as formaldehyde, formic acid and NO_2 compared to the use of only one or two stages.

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‡LPP, Ecole Polytechnique, Palaiseau, France.
§INP-Greifswald, Greifswald, Germany.

14:45

PR3 6 Physical-chemical characterization of nitrogen atmospheric pressure plasma jets* SYLWIA PTASINSKA, MATEJ KLAS, *University of Notre Dame* Most of atmospheric pressure plasma jet (APPJ) sources operate with noble gases as the feed gas, which require lower breakdown voltage than typical molecular gases in order to ignite the plasma. However, a high consumption of expensive noble gases during long term plasma operation in many applications increases costs of usage. Therefore, the development of new sources working with less expensive gases such as nitrogen or air is needed. In this work we concentrated on electrical, optical and thermal characterization of two nitrogen plasma jet

sources. Both APPJ sources have been constructed with the same materials and dimensions, the only difference is the shape of the electrodes: spiral and 4-strip. This distinction is responsible for different electrical, optical and thermal properties of plasma jets, which will be reported at the meeting. It has been also observed that by adding specific amount of oxygen to the N_2 flow the production of different species such as NO or ON_2 excimer can be controlled.

SESSION PR5: ELECTRON COLLISIONS WITH ATOMS AND MOLECULES I
Thursday Afternoon, 3 October 2013; Room: Village Square at 13:30; Tom Rescigno, Lawrence Berkeley National Laboratory, presiding

Invited Papers

13:30

PR5 1 Large-scale B-spline R-matrix calculations of electron impact excitation and ionization processes in complex atoms*
OLEG ZATSARINNY, *Drake University*

In recent years, the B-spline R-matrix (BSR) method [1] has been applied to the treatment of a large number of atomic structure and electron-atom collision problems. Characteristic features of the BSR approach include the use of B-splines as a universal basis to describe the projectile electron inside the R-matrix box and the employment of term-dependent, and hence non-orthogonal, orbitals to construct the target states. The latter flexibility has proven to be of crucial importance for complex targets with several partially filled subshells. The published computer code [2] has since been updated and extended to allow for a fully relativistic description at the level of the Dirac-Coulomb hamiltonian. Also, the systematic inclusion of a large number of pseudo-states in the close-coupling expansion has made it possible to extend the range of applicability from elastic and inelastic low-energy near-threshold phenomena to intermediate energies (up to several times the ionization threshold) and, in particular, to describe ionization processes as well. The basic ideas of the BSR approach will be reviewed, and its application will be illustrated for a variety of targets. Particular emphasis will be placed on systems of relevance for applications in gaseous electronics, such as the generation of complete datasets for electron collisions with the heavy noble gases Ne-Xe. Many of our data, which are needed for the description of transport processes in plasmas, are available through the LXCat database [3].

[1]O. Zatsarinny and K. Bartschat. J. Phys. B **46** (2013) 112001.
[2]O. Zatsarinny, Comp. Phys. Commun. **174** (2006) 273.
[3]http://www.lxcat.laplace.univ-tlse.fr/database.php

Contributed Papers

14:00

PR5 2 Electron Impaction Ionisation from Laser Aligned Magnesium KATE NIXON, ANDREW MURRAY, *The University of Manchester* GREGORY ARMSTRONG, JAMES COLGAN, *Los Alamos National Laboratories* Very recently, major advances have been made in theoretical predications of electron impact ionisation from molecular targets at low energies [1]. This has been achieved by averaging a number of cross sections, each calculated for a discrete target orientation. The accuracy of the individual cross sections is however still untested. Obtaining experimental data for molecular targets of a known orientation is difficult, and has only been achieved in a few studies for diatomic molecules [2-4]. Atomic targets can also be used to characterise the influence of alignment on the electron impact ionisation. In these studies laser radiation excites an atom to a P state and, more importantly, control the ori-

entation of the electron density within the atom, as demonstrated by Nixon and Murray [5]. New experimental results for magnesium will be presented where the target alignment is varied within the scattering plane. These results will be accompanied by theoretical predictions from new time dependant close coupling (TDCC) calculations.

[1]D Madison, personal communications.
[2]M Takahashi *et al.* 2005 PRL **94** 213202.
[3]A Senftleben *et al.* 2010 J. Chem. Phys. **133** 1.
[4]S Bellm *et al.* 2010 PRL **104** 023202.
[5]KL Nixon and AJ Murray 2011 PRL **106** 12320.

14:15

PR5 3 Triple Differential Cross Sections for Ionization of Laser-Aligned Mg Atoms by electron impact* SADEK AMAMI, DON MADISON, *Missouri University of Science and Technology, Rolla,*

Mo, USA **KATE NIXON, ANDREW MURRAY,** *University of Manchester, Manchester, United Kingdom* 3DW (3-body distorted wave) triple differential cross sections have been calculated for electron impact ionization of magnesium atoms aligned by lasers. Calculations have been performed for the kinematics of the experiment performed by Kate Nixon and Andrew Murray at Manchester, England [K. L. Nixon and A. J. Murray 2011 Phys. Rev. Lett. **106**, 123201]. An incident projectile was produced with energy of 41.91eV, scattered and ejected electrons were detected with equal energies (E1=E2=20eV), the scattered projectile was detected at a fixed angle of 30deg, and the ejected electrons were detected at angles ranging between $0° - 180°$. The theoretical 3DW results will be compared with the experimental data.

Invited Papers

14:30
PR5 4 Accuracy of Theoretical OAMO Calculations for Electron-Impact Ionization of Molecules*
HARI CHALUVADI, *Missouri University of Science and Technology*

The study of electron impact single ionization of atoms and molecules has provided valuable information about fundamental collisions. The most detailed information is obtained from triple differential cross sections (TDCS) in which the energy and momentum of all three final state particles are determined. These cross sections are much more difficult for theory since the detailed kinematics of the experiment become important. There are many theoretical approximations for ionization of molecules. One of the successful methods is the distorted wave (DW) approximation. One of the strengths of the DW approximation is that it can be applied for any energy and any size molecule. One of the approximations that has been made to significantly reduce the required computer time is the OAMO (orientation averaged molecular orbital) approximation. Surprisingly, the M3DW-OAMO approximation yields reasonably good agreement with experiment for ionization of H_2 by both low and intermediate energy incident electrons. On the other hand, the M3DW-OAMO results for ionization of CH_4 [1,2] and NH_3 [3] did not agree very well with experiment. Consequently, we decided to check the validity of the OAMO approximation by performing a proper average over orientations and we found much better agreement with experimental data. In this talk we will show the current status of agreement between experiment and theory for low and intermediate energy single ionization of small, medium, and large molecules.

[1]Nixon *et al.*, 2012 J.Chem. Phys. **136**, 094302.
[2]Xu *et al.*, 2012 J. Chem. Phys. **137**, 024301.
[3]Nixon *et al.*, 2013 J. Chem. Phys. **138**, 174304.

SESSION QR1: MICROWAVE DISCHARGES II
Thursday Afternoon, 3 October 2013
Room: Ballroom I at 15:30
Alok Ranjan, TEL Technology Center America, presiding

Contributed Papers

15:30
QR1 1 Investigation of Microplasma Instabilities at 1 GHz*
CHEN WU, JEFFREY HOPWOOD, *Tufts University* Microwave microplasmas have been operated stably in excess of 2000 hours using less than one watt of power. Plasmas at atmospheric pressure and high power density, however, are subject to ionization overheating instability followed by a destructive glow-to-arc transition. We describe steady-state atmospheric pressure microplasmas in non-flowing argon and air driven by up to 40 watts of microwave power. These discharges are supported by either a quarter-wave microstrip resonator or a microstrip transmission line. Models show that the resonator configuration rejects excess power and remains unconditionally stable. The transmission line, however, couples power efficiently to a plasma of $\sim 100\ \Omega$ and produces a more intense discharge. Electrodes of copper, aluminum and lead-based solder are investigated on both polymer and alumina substrates. Copper and lead electrodes may be evaporated by a high power microdischarge as seen by optical emission. These conditions uniquely result in severe electrode damage. Microdischarges supported on polymer substrates show C_2, CN and CH emission but alumina substrates are unaffected by the microplasma. These results show that steady-state microwave discharges can be stable at very high power density provided that copper microelectrodes and ceramic substrates are employed.

15:45
QR1 2 VUV Photon Fluxes from Microwave Excited Microplasmas at Low Pressure **PENG TIAN,** *University of Michigan* **MARK DENNING, RANDALL URDHAL,** *Agilent Technologies* **MARK J. KUSHNER,** *University of Michigan* Microplasmas in rare gases and rare gases mixtures can provide efficient and discretely tunable sources of VUV light. Microwave excited microplasma sources excited by a split-ring resonator antenna in rare gas mixtures operated in ceramic cavities with sub-mm dimensions have been developed as discretely tunable VUV sources for chemical analysis. Controlling wavelengths and the ratio of ion to VUV fluxes are important to achieving chemical selectivity. In this paper, we will discuss results from an investigation of scaling laws for the efficiency of VUV photon production in rare gas mixtures. The investigation was performed using a hydrodynamics model where the electron energy distribution and radiation transport are addressed by Monte Carlo simulations. Plasma density, VUV photon production and fluxes from the cavities will be discussed for mixtures of Ar, He, Xe, Kr,

and as a function of power format (pulsing, cw), pressure and cavity sizes.

16:00

QR1 3 Time-resolved microplasma excitation temperature in a pulsed microwave discharge* JEFFREY HOPWOOD, SHABNAM MONFARED, ALAN HOSKINSON, *Tufts University* Microwave-driven microplasmas are usually operated in a steady-state mode such that the electron temperature is constant in time. Transient measurements of excitation temperature and helium emission lines, however, suggest that short microwave pulses can be used to raise the electron energy by 20-30% for approximately 100 ns. Time-resolved optical emission spectrometry reveals an initial burst of light emission from the igniting microplasma. This emission overshoot is also correlated with a measured increase in excitation temperature. Excimer emission lags atomic emission, however, and does not overshoot. A simple model demonstrates that an increase in electron temperature is responsible for the overshoot of atomic optical emission at the beginning of each microwave pulse. The formation of dimers and subsequent excimer emission requires slower three-body collisions with the excited rare gas atom; this is why excimer emission does not overshoot the steady state value. Similar experimental and modeling results are observed in argon gas. The overshoot in electron temperature may be used to manipulate the collisional production of species in microplasmas using short, low-duty cycle microwave pulses.

16:15

QR1 4 Harmonic Generation by Microwave-frequency Microplasma* STEPHEN PARSONS, ALAN HOSKINSON, JEFFREY HOPWOOD, *Tufts University* A microplasma may operate as a nonlinear circuit element and generate power at the harmonics of the drive frequency. As an example, microplasma is sustained using 1 W of power at 1.3 GHz in a small discharge gap formed in a split-ring resonator. A probe extends into the microplasma and extracts the 3rd harmonic power through a tuned resonator at 3.9 GHz. The experimental data show that this non-optimized system produces a +38 dB increase in 3rd harmonic power in the presence of a microplasma. Two origins of nonlinearity are described: the harmonic conduction current due to electron collection by microelectrodes, and the harmonic displacement current due to the voltage-dependent sheath capacitance. PIC-MC simulations suggest that the microplasma nonlinearity may also be exploited at frequencies of 100 GHz.

16:30

QR1 5 Microwave-driven plasmas in Hollow-Core Photonic Crystal Fibres* L.L. ALVES, *IPFN/IST-UTL, Portugal* O. LEROY, C. BOISSE-LAPORTE, P. LEPRINCE, *LPGP-UPS/CNRS, France* B. DEBORD, F. GEROME, R. JAMIER, F. BENABID, *GPPMM/XLIM, CNRS-UNILIM, France* This paper reports on a novel solution to ignite and maintain micro-plasmas in gas-filled Hollow-Core Photonic Crystal Fibres (HC-PCFs), using CW microwave excitation (2.45 GHz) [1]. The original concept is based on a surfatron, generating argon micro-plasmas of few centimetres in length within a 100 μm core-diameter Kagome HC-PCF, at ~1 mbar on-gap gas-pressure using low powers (< 50 W). Diagnostics of the coupled power evidence high ionization degrees ($\sim 10^{-2}$), for moderate gas temperatures ($\sim$1300 K at the centre of the fibre, estimated by OES), with no damage to the host structure. This counter intuitive result is studied using a 1D-radial fluid model that describes the charged particle and the electron energy transport, the electromagnetic excitation and the gas heating [2,3]. We analyze the modification of the plasma and the gas heating mechanisms with changes in the work conditions (core diameter, pressure and electron density).

[1] B. Debord *et al.*, ECOC conference Mo.2.LeCervin.5. (2011).
[2] L.L. Alves *et al.*, Phys. Rev. E **79**, 016403 (2009).
[3] J. Gregório *et al.*, Plasma Sources Sci. Technol. **21**, 015013 (2012).

SESSION QR2: CAPACITIVELY COUPLED PLASMAS II

Thursday Afternoon, 3 October 2013; Room: Ballroom II at 15:30; Ikuo Sawada, Tokyo Electron U.S., presiding

Invited Papers

15:30

QR2 1 Electron heating in capacitively coupled plasmas revisited: single and multi-frequency discharges
TREVOR LAFLEUR, *LPP-CNRS, Ecole Polytechnique*

Using particle-in-cell (PIC) simulations, we re-analyse the mechanism of electron heating in low pressure capacitively coupled plasmas (CCPs). After equilibrium has been reached in the simulations, spatio-temporal moments of the electron distribution function are taken within the rf cycle, and from this the density, current, pressure, and momentum loss due to collisions, of the electrons is found in the discharge. With these moments we then reconstruct each term in the electron fluid mechanical energy conservation equation, so as to explicitly analyse the power deposition process. We perform simulations for both single frequency sinusoidal discharges, and also for more recent multi-frequency, or "tailored voltage waveform" driven discharges. The single frequency (13.56 MHz) simulations are modelled on the original experiments in Argon performed by Godyak, showing the transition from a bi-Maxwellian distribution function at low pressure (below 200 mTorr) to a Druyvestyen-type distribution at high pressures (above 400 mTorr). The results of the PIC moment analysis shows that only two terms in the fluid conservation equation contribute a net power deposition: a term accounting for collisional power absorption, and a term accounting for pressure heating. The latter term is dominant at low pressures, while the former is dominant at higher pressures. We find however that the collisional heating is almost always significant, and even at the lowest pressure, accounts for about 40% of the total power absorption. By comparing the electron momentum

loss due to collisions with that usually used in analytical sheath models, we find a significant difference at low pressures, which cannot be explained by conventional local kinetic theories based on the two-term expansion of the Boltzmann equation. The moment analysis is repeated for the multi-frequency discharges, where we obtain similar results: collisional power absorption is always observed to be significant, even at the lowest pressures simulated (20 mTorr). However the generation of a bias voltage due to the electrical asymmetry effect, and consequently the unequal division of the sheath voltages, causes high frequency oscillations to develop in the plasma at frequencies more than an order of magnitude higher than the applied rf frequencies. These so-called nonlinear plasma series resonance oscillations are found to enhance both the collisional and pressure heating, and for sufficiently large applied voltages, an additional heating mechanism is identified associated with the electron inertial terms in the conservation equation.

Contributed Papers

16:00

QR2 2 Electron heating and control of ion properties in capacitive discharges driven by customized voltage waveforms JULIAN SCHULZE, *Ruhr-University Bochum* ARANKA DERZSI, IHOR KOROLOV, *Hungarian Academy of Sciences* EDMUND SCHUENGEL, *Ruhr-University Bochum* ZOLTAN DONKO, *Hungarian Academy of Sciences* We investigate the electron heating dynamics in capacitive radio frequency plasmas driven by customized voltage waveforms and study the effects of modifying this waveform on the DC self-bias, η, the ion flux, Γ_i, and the mean ion energy, E_i, at the electrodes by PIC simulations. The driving voltage waveform is customized by adding N consecutive harmonics (N $\leq$ 4) of 13.56 MHz with specific harmonics' amplitudes and phases. In an argon plasma, we find η to be generated via the Electrical Asymmetry Effect for N $\geq$ 2. η can be controlled by adjusting the harmonics' phases and is enhanced by adding more consecutive harmonics. At 3 Pa, the discharge is operated in the α-mode and E_i can be controlled by adjusting the phases at constant Γ_i. The ion flux can be increased by adding more harmonics due to the enhanced electron sheath heating. However, we find E_i not to remain constant as a function of N at both electrodes due to a change of η as a function of N. At 100 Pa and using a high secondary electron emission coefficient of $\gamma = 0.4$, the discharge is operated in the γ-mode. Due to this mode transition and the specific ionization dynamics in the γ-mode, Γ_i is no longer constant as a function of the harmonics' phases and decreases with increasing N.

16:15

QR2 3 Student Award Finalist - The role of surface properties in the dynamics of radio-frequency plasma sheaths: measurements and simulations ARTHUR GREB, *York Plasma Institute, Department of Physics, University of York, York, YO10 5DD, UK* ANDREW GIBSON, *Centre for Plasma Physics, Queen's University Belfast, Belfast, BT7 1NN, UK* KARI NIEMI, DEBORAH O'CONNELL, TIMO GANS, *York Plasma Institute, Department of Physics, University of York, York, YO10 5DD, UK* Plasma processing on an industrial scale is becoming increasingly complex and now demands new strategies for process metrology. Of particular interest is the energy transport in the interface region between non-equilibrium low-pressure plasma and the surface. Experimental measurements are coupled to a benchmarked 1D fluid model, with improved energy dependent treatment of ion mobilities, for a geometrically asymmetric capacitively coupled oxygen rf discharge [1]. Within a pressure range of 10 − 100 Pa the simulations predict that changing surface conditions have a significant effect on the surface loss probability and lifetime of metastable oxygen, and consequently electronegativity, as well as the secondary electron emission coefficient. These substantially influence the plasma sheath dynamics on a nanosecond timescale. For different surface materials, we confirm our findings by comparing excitation features obtained from simulations with phase resolved optical emission spectroscopy measurements. This allows us to develop new metrology concepts to monitor and control plasma-surface interaction processes in real-time. The authors thank Intel Ireland, Ltd. for supporting this research.

[1]A. Greb *et al.*, Phys. Plasmas 20 (2013).

16:30

QR2 4 An Analytical Model for the Radio-Frequency Sheath UWE CZARNETZKI, *Ruhr-University Bochum, Faculty for Physics and Astronomy* An analytical model for the planar radio frequency (RF) sheath in capacitive discharges is developed based on the applied RF voltage as the boundary condition. In a first step, the individual sheath voltages and the self-bias are calculated using a cubic-charge voltage relation. In the second step, a single integro-differential equation is derived to describe the ion flow velocity in the sheath under all conditions of collisionality. Central to the model is the screening function that describes the screening of the ion density by the mean electron density in the sheath. Numerical integration of the sheath equation is straight forward. However, for the collisionless as well as the collisional case explicit, simple, and precise analytical approximations can be found. Drift velocities, densities, fields, currents, and charge-voltage relations are calculated. Further, the Child-Langmuir laws for both cases of collisonality are derived. These solutions are in very good agreement with experimental data from the literature based on laser electric field measurements, the Brinkmann sheath model, and PIC simulations. The technique works well also for other waveforms, e.g. the electrical asymmetry effect or tailored pulse waveforms.

16:45

QR2 5 Transient plasma parameters in pulsed RF CCP discharges* THERESA KUMMERER, *NC State University* DAVID COUMOU, *MKS Instruments* STEVEN SHANNON, *NC State University* Low pressure plasmas driven by kHz pulsed RF power sources provide very unique conditions for materials processing. The electrical transients generated by these rapid pulses present unique challenges for efficient power delivery and control; these challenges are compounded further in systems with multiple power sources. To advance closed loop control of power delivery through these transients and further advance pulsed RF power delivery, a detailed study of plasma conditions during the on and off transitions in the pulse cycle has been carried out. Time resolved Langmuir probe, OES, and gated CCD images are combined with high time resolution in-line RF metrology to study changes in plasma conditions and their impact on discharge impedance and power delivery for both single and multiple independent RF source configurations. By correlating plasma parameters with electrical measurement, an extension of existing empirical models that measure plasma parameters through RF measurement is made. This extended model will provide time resolved plasma parameters within the pulse cycle, enabling pulse parameter optimization (pulse frequency, duty cycle, etc.) for critical processes using in-situ diagnosis.

SESSION QR3: MAGNETICALLY ENHANCED PLASMAS
Thursday Afternoon, 3 October 2013; Room: Nassau Room at 15:30; Ben Longmier, University of Michigan, presiding

Invited Papers

15:30
QR3 1 Plasma regimes in high power pulsed magnetron sputtering*
TERESA DE LOS ARCOS,[†] *Ruhr-Universität Bochum*

High Power Pulsed Magnetron Sputtering (HPPMS) is a relatively recent variation of magnetron sputtering where high power is applied to the magnetron in short pulses. The result is the formation of dense transient plasmas with a high fraction of ionized species, ideally leading to better control of film growth through substrate bias. However, the broad range of experimental conditions accessible in pulsed discharges results in bewildering variations in current and voltage pulse shapes, pulse power densities, etc, which represent different discharge behaviors, making it difficult to identify relevant deposition conditions. The complexity of the plasma dynamics is evident. Within each pulse, plasma characteristics such as plasma composition, density, gas rarefaction, spatial distribution, degree of self-sputtering, etc. vary with time. A recent development has been the discovery that the plasma emission can self-organize into well-defined regions of high and low plasma emissivity above the racetrack (spokes), which rotate in the direction given by the E×B drift and that significantly influence the transport mechanisms in HPPMS. One seemingly universal characteristic of HPPMS plasmas is the existence of well defined plasma regimes for different power ranges. These regimes are clearly differentiated in terms of plasma conductivity, plasma composition and spatial plasma self-organization. We will discuss the global characteristics of these regimes in terms of current-voltage characteristics, energy-resolved QMS and OES analysis, and fast imaging. In particular we will discuss how the reorganization of the plasma emission into spokes is associated only to specific regimes of high plasma conductivity. We will also briefly discuss the role of the target in shaping the characteristics of the HPPMS plasma, since sputtering is a surface-driven process.

[†]Research Department Plasmas with Complex Interactions, Institute of Experimental Physics II.

Contributed Papers

16:00
QR3 2 Sensitivity analysis via kinetic global modeling of rotating spokes in HiPIMS* SARA GALLIAN, JAN TRIESCHMANN, THOMAS MUSSENBROCK, *Ruhr University Bochum* WILLIAM N.G. HITCHON, *University of Wisconsin-Madison* RALF PETER BRINKMANN, *Ruhr University Bochum* High Power Impulse Magnetron Sputtering discharges are characterized by high density plasma (peak electron density 10^{18} - 10^{20} m^{-3}) in a strong magnetic field (100 mT), with highly energetic secondary electrons (500 - 1000 eV). The combination of these factors results in a discharge showing a vast range of instabilities, in particular, a single rotating high emissivity region is often observed. This highly ionized region -or spoke- shows a stationary behavior in the current plateau region and rotates with $\Omega \approx$ kHz.[†] We apply a global model that evolves the electron energy distribution function self-consistently with the rate equations for Ar and Al species. The volume average is performed *only* in the structure region and a net neutral flux term is imposed to model the spoke rotation. Outside the spoke region, the neutral densities are evolved according to a phenomenological fluid model.[‡] The model is solved using a relaxation method. We present a sensitivity analysis of the resulting steady state on the different physical mechanisms and comment on the anomalous electron transport observed.

[†]A. Hecimovic *et al.* (2013), submitted.
[‡]S. Gallian *et al.* (2013), submitted.

16:15
QR3 3 Kinetic simulation of neutral particle transport in sputtering processes* JAN TRIESCHMANN, SARA GALLIAN, RALF PETER BRINKMANN, THOMAS MUSSENBROCK, *Institute of Theoretical Electrical Engineering, Ruhr University Bochum* STEFAN RIES, NIKITA BIBINOV, PETER AWAKOWICZ, *Institute for Electrical Engineering and Plasma Technology, Ruhr University Bochum* For many physical vapor deposition applications using sputtering processes, knowledge about the detailed spatial and temporal evolution of the involved gas species is of great importance. Modeling of the involved gas dynamic and plasma processes is however challenging, because the operating pressure is typically below 1 Pa. In consequence, only kinetic descriptions are appropriate. In order to approach this problem, the dynamics of sputtered particle transport through a neutral gas background is simulated. For this study, a modified version of the three-dimensional Direct Simulation Monte Carlo (DSMC) code *dsmcFoam* [1] is utilized. The impact of a transient sputtering wind is investigated in a generic reactor geometry, which may be used for dc Magnetron Sputtering (dcMS), High Power Impulse Magnetron Sputtering (HiPIMS), as well as sputtering in capacitively coupled discharges. In the present work a rarefaction of the background gas is observed. Moreover in pulsed mode the temporal dynamics of the rarefaction and subsequent recovery of the background gas is investigated.

[1]T.J. Scanlon *et al.*, Computers and Fluids **39**, 2078–2089 (2010).

16:30
QR3 4 Effect of anomalous electron cross-field transport on electron energy distribution function in a DC-RF magnetized plasma discharge* YEVGENY RAITSES, *Princeton Plasma Physics Laboratory, Princeton, NJ* VINCENT DONNELLY, *University of Houston, Houston, TX* IGOR KAGANOVICH, *Princeton Plasma Physics Laboratory, Princeton, NJ* VALERY GODYAK,

University of Michigan, Ann Arbor, MI The application of the magnetic field in a low pressure plasma can cause a spatial separation of cold and hot electron groups. This so-called magnetic filter effect is not well understood and is the subject of our studies. In this work, we investigate electron energy distribution function in a DC-RF plasma discharge with crossed electric and magnetic field operating at sub-mtorr pressure range of xenon gas [1]. Experimental studies showed that the increase of the magnetic field leads to a more uniform profile of the electron temperature across the magnetic field. This surprising result indicates the importance of anomalous electron transport that causes mixing of hot and cold electrons. High-speed imaging and probe measurements revealed a coherent structure rotating in E cross B direction with frequency of a few kHz. Similar to spoke oscillations reported for Hall thrusters [2], this rotating structure conducts the largest fraction of the cross-field current.

[1] Y. Raitses, J. K. Hendryx, and N. J. Fisch, IEPC-2009-024, in the Proceedings of the 31st International Electric Propulsion Conference, September, 2009, Ann Arbor, MI.

[2] C. L. Ellison, Y. Raitses and N. J. Fisch, Phys. Plasmas **19**, 013503 (2012).

16:45

QR3 5 Proof of principle experiments for helicon discharges in hydrogen STEFAN BRIEFI, URSEL FANTZ, *Max-Planck-Institut für Plasmaphysik, EURATOM-Assoziation, Boltzmannstr. 2, 85748*

Garching, Germany In order to reduce the amount of power required for generating CW hydrogen discharges with high electron densities and a high degree of dissociation via RF coupling, the helicon concept is investigated. For this purpose a small laboratory experiment (length of the discharge vessel 40 cm, diameter 10 cm) has been built up. The RF generator has a maximum power of 600 W (frequency 13.56 MHz) and a Nagoya type III antenna is applied. As water cooling was avoided in constructing the experiment for simplicity, the induction coils can only generate a rather low magnetic field up to 14 mT. The performed investigations cover a variation of the RF power and the magnetic field in a pressure range between 0.3 and 10 Pa. Around a magnetic field of 3 mT the low field peak which is typical for helicon discharges could be observed. As the high density mode of helicon discharges has not yet been reached, a different RF generator (2 MHz, 2 KW) and water cooled induction coils will be applied in a next step in order to increase the available power and the magnetic field.

SESSION RR1: RECEPTION/BANQUET
Thursday Evening, 3 October 2013
Room: Ballroom at 19:00

Contributed Papers

19:00

RR1 1 Reception/Banquet

SESSION SF1: PLASMAS FOR NANOTECHNOLOGIES
Friday Morning, 4 October 2013; Room: Ballroom I at 8:30; Tomohiro Nozaki, Tokyo Institute of Technology, presiding

Invited Papers

8:30
SF1 1 Microplasma synthesis of sub-5 nm metal clusters: A novel platform for study and discovery*
R. MOHAN SANKARAN, *Case Western Reserve University*

Homogeneous, gas-phase nucleation of particles in reactive plasmas is well known. Dust formation in chemical vapor deposition (CVD) processes is undesired and can lead to deleterious effects on device fabrication and performance [1]. Recently, plasma systems have been developed to purposefully synthesize nanoparticles for technological applications [2]. The advantage of plasmas over other chemical methods include the high purity, uniformity of particle size, and the possibility of accessing unique chemistries through the non-equilibrium environment. In this talk, I will present our contribution to this rapidly emerging field: the development of a new class of atmospheric-pressure, low-temperature microplasma systems that enables the synthesis of unagglomerated, sub-5 nm particles in a single step. The synthesis of clusters in this size range is of current interest for the study and discovery of novel nanomaterials. To illustrate this point, two examples will be presented. One, clusters of Ni, Fe, and other metals are produced from their corresponding organometallic precursors [3]. Alloys with precisely controlled compositions are also obtained by tuning the relative amount of the precursors in the plasma phase. The availability of metal clusters with well-defined size and composition has allowed us to systematically study carbon nanotube nucleation and growth, and relate the properties of the catalyst to the as-grown tube diameter and chirality [4]. Two, we have carried out studies of carbon cluster formation and observed the presence of diamond-phase carbon [5]. The nucleation of diamond at near ambient conditions supports theoretical predictions of the stability of sp^3 diamond over sp^2 carbon and suggests a potential route for their existence in the cosmos.

[1] M. Shiratani *et al.*, Jap. J. Appl. Phys. **30**, 1887 (1991).
[2] U. Kortshagen, J. Phys. D **42**, 113001 (2009).
[3] P. A. Lin, Angew. Chem. Int. Ed. **50**, 10953 (2011).
[4] W-H. Chiang *et al.*, Nat. Mater. **8**, 882 (2009).
[5] A. Kumar *et al.*, submitted.

Contributed Papers

9:00
SF1 2 Synthesis and investigation of reaction mechanisms of diamondoids obtained by dielectric barrier discharge microplasma reactors operated in adamantane - argon - methane - hydrogen mixtures at atmospheric pressure* SVEN STAUSS, CHIKAKO ISHII, *The University of Tokyo* DAVID Z. PAI, *Institut Pprime CNRS UPR 3346, Université de Poitiers, ENSMA* KAZUO TERASHIMA, *The University of Tokyo* Diamondoids, sp^3 hybridized molecules consisting of a cage-like carbon framework with hydrogen terminations, hold promise for many applications: biotechnology, medicine, and opto- and nanoelectronics. So far, diamondoids consisting of more than four cage units have been synthesized by electric discharge and pulsed laser plasmas in supercritical fluids, but the generation of plasmas in high-pressure media is not straightforward. Here we present an alternative, continuous flow process, where diamondoids are synthesized by dielectric barrier discharges inside microreactors. The plasmas were generated at peak-to-peak voltages of 3 - 4 kV at a frequency of 10 kHz, in Ar (96 - 100%-vol) - methane (0 - 4%-vol) - hydrogen (0 - 4%-vol) mixtures, at atmospheric pressure and flow rates of 2 - 20 sccm. As a precursor we used the first diamondoid, adamantane, whose density was controlled by adjusting the reactor temperature in the range from 293 to 323 K. Gas chromatography - mass spectrometry analysis indicated the synthesis of the second diamondoid, diamantane, and the presence of alkylated adamantane derivatives suggests a stepwise reaction mechanism. We will also discuss the influence of the plasma gas composition and precursor density on the diamondoid synthesis.

9:15
SF1 3 Synthesis of group IV quantum confined nanocrystals using a scalable atmospheric pressure plasma reactor SADEGH ASKARI, PAUL MGUIRE, DAVIDE MARIOTTI, *Nanotechnology & Integrated Bio-Engineering Centre (NIBEC), University of Ulster, BT37 0QB, UK* PLASMA SCIENCE AND NANOSCALE ENGINEERING GROUP TEAM Group IV semiconductor nanocrystals (NCs) have acquired much interest for a wide range of applications including photovoltaic cells and light emitting devices. However synthesis of covalently bonded semiconductors of group IV nanoparticles with crystalline structure remains challenging due to the higher crystallization temperatures compared to other semiconductors such as group II-VI materials. We present our results on the synthesis of Si and SiC NCs in a scalable atmospheric-pressure plasma reactor. Liquid and gas precursors such as tetramethylsilane and silane have been used, and nanoparticles can be collected directly in liquids or on substrates to form films of NCs. Si and SiC NCs have been characterized by transmission electron microscopy, x-ray photoelectron spectroscopy and also by ultarviolet-visible absorption and photoluminescenc measurements. The reactor configuration has been designed to improve the control of important parameters such as NCs residence time and throughput so that future developments can easily lead to scalable configurations for

industrial-scale nanoparticle manufacturing without varying the plasma conditions.

9:30

SF1 4 Atmospheric Pressure Microplasma for Post-Synthesis Treatment of Silicon Nanocrystals for Photovoltaic Applications TAMILSELVAN VELUSAMY, CONOR ROCKS, SOMAK MITRA, *Nanotechnology & Integrated Bio-Engineering Centre (NIBEC), University of Ulster, Jordanstown, UK* VLADIMIR SVRCEK, *Research Center for Photovoltaic Technologies, AIST, Tsukuba, 305-8568, Japan* PAUL MAGUIRE, DAVIDE MARIOTTI, *Nanotechnology & Integrated Bio-Engineering Centre (NIBEC), University of Ulster, Jordanstown, UK* VLADIMIR SVRCEK COLLABORATION We report the effects of plasma treatment on the optoelectronic properties of silicon nanocrystals (SiNCs) synthesized by electrochemical etching. A simple atmospheric pressure microplasma is used to tailor the functionalization of SiNCs and improve their characteristics in films. The SiNCs are spin coated on glass substrates at different thickness and the effects of the microplasma treatment on the SiNCs in liquid and in films are investigated. The surface chemistry induced by the plasma treatment is also studied and possible plasma-activated mechanisms are suggested. In order to assess the effects of the plasma treatment we perform ultraviolet-visible absorption and photoluminescence measurements together with kelvin probe and electrical measurements of the films.

9:45

SF1 5 Cluster control plasma CVD for fabrication of stable a-Si:H solar cells* MASAHARU SHIRATANI, YUUJI HASHIMOTO, YOSHINORI KANEMITSU, HYUNWOONG SEO, KUNIHIRO KAMATAKI, GIICHIRO UCHIDA, NAHO ITAGAKI, KAZUNORI KOGA, *Kyushu University* Light-induced degradation of a-Si:H is the key issue for a-Si:H solar cells, because light exposure initially causes a significant reduction of the efficiency of the cells due to the degradation. In SiH4 discharges employed for a-Si:H deposition, there coexist three deposition precursors; SiH3 radicals, HOS radicals, and amorphous clusters (nanoparticles) [1]. SiH3 radicals are the main deposition precursors for "good" quality films, whereas clusters are the precursors to cause the light induced degradation. To suppress cluster incorporation into films, we employ, 1) magnetic field which modifies EEDF, 2) gas heating to suppress polymerization reactions in gas phase, 3) gas flow which drives clusters downstream, 4) thermophoretic force which supresses cluster deposition, and 5) a cluster eliminating filter. Our a-Si:H films deposited at 3 nm/s show a low stabilized defect density of 5×10^{15} cm^{-3}. To evaluate their quality as an I layer of PIN solar cells, we have measured Fill Factor (FF) of N-type c-Si/a-Si:H/Ni Schottky cells of such cluster-free a-Si:H films. Our cell shows high initial FF of 0.516, high stable FF of 0.514, and little light induced degradation ratio of 0.39%.

*Work supported by NEDO, PVTEC, and MEXT.

[1] Y. Kim *et al.*, Jpn. J. App. Phys. **52** (2013) 01AD01.

SESSION SF2: PLASMA DEPOSITION
Friday Morning, 4 October 2013; Room: Ballroom II at 8:30; Hirotaka Toyoda, Nagoya University, presiding

Invited Papers

8:30

SF2 1 Novel plasma catalytic reaction for structural-controlled growth of graphene and graphene nanoribbon
TOSHIAKI KATO, *Department of Electronic Engineering, Tohoku University*

An advanced plasma chemical vapor deposition (CVD) method has outstanding advantages for the structural-controlled growth and functionalization of carbon nanotubes (CNTs) [1,2] and graphene [3,4]. Graphene nanoribbons combine the unique electronic and spin properties of graphene with a transport gap. This makes them an attractive candidate material for the channels of next-generation transistors. However, the reliable site and alignment control of nanoribbons with high on/off current ratios remains a challenge. We have developed a new, simple, scalable method based on novel plasma catalytic reaction for directly fabricating narrow (23 nm) graphene nanoribbon devices with a clear transport gap (58.5 meV) and a high on/off ratio (10000). Indeed, graphene nanoribbons can be grown at any desired position on an insulating substrate without any post-growth treatment, and large-scale, two- and three dimensional integration of graphene nanoribbon devices should be realizable, thereby accelerating the practical evolution of graphene nanoribbon-based electrical applications [5].

[1] T. Kato and R. Hatakeyama, J. Am. Chem. Soc. **130**, 8101 (2008).
[2] T. Kato and R. Hatakeyama, ACS Nano **4**, 7395 (2010).
[3] T. Kato, L. Jiao, X. Wang, H. Wang, X. Li, L. Zhang, R. Hatakeyama, and H. Dai, Small **7**, 574 (2011).
[4] T. Kato and R. Hatakeyama, ACS Nano **6**, 8508 (2012).
[5] T. Kato and R. Hatakeyama, Nature Nanotechnology **7**, 651 (2012).

Contributed Papers

9:00

SF2 2 A Source of Metal Vapor and Pulsed Beams of High-Energy Gas Molecules ALEXANDER METEL, VASILY BOLBUKOV, MARINA VOLOSOVA, SERGEI GRIGORIEV, YURY MELNIK, *Moscow State University of Technology "STANKIN"* DEPARTMENT OF HIGH-EFFICIENCY MACHINING TECH-NOLOGIES TEAM Application to a substrate of negative high-voltage pulses results in 0.1-mm-thick nc-Ti$_2$N/nc-TiN nanocomposite tough and superhard coatings with an interface width exceeding 5 μm. For production of such coatings on complex-shaped dielectric products a source of broad pulsed beams of high-energy gas molecules has been developed the molecule trajectories coinciding with those of slow metal atoms produced due to sputtering a target by ions accelerated from the ion emitter of the source. The

atoms pass through the emitter and together with gas ions enter the process chamber through the emissive grid. The emitter is produced at the gas pressure 0.2-0.5 Pa by glow discharge with confinement of electrons in an electrostatic trap formed by the grid and a cold hollow cathode. Specialty of the source is that the ion emitter potential is equal to zero, negative high-voltage pulses are applied to the grid and high-energy gas molecules are produced due to charge-exchange collisions in two space-charge sheaths: first between the emitter and the grid and then between the grid and the secondary plasma.

9:15
SF2 3 Diagnostics and Monitoring of a Plasma Beam Source based on Optical Emission Spectroscopy* JENS HARHAUSEN, RÜDIGER FOEST, DETLEF LOFFHAGEN, ANDREAS OHL, JAN SCHÄFER, *Leibniz Institute for Plasma Science and Technology* Plasma ion assisted deposition (PIAD) is employed for the production of high performance optical coatings. Here, the assist-source is a hot cathode DC discharge (Advanced Plasma Source APS) which generates an ion beam (ion energy $E_i \sim 50$-$150\,eV$) based on an expansion process at a chamber pressure of $p \sim 20\,mPa$. Efforts in plasma characterization have been made to improve the PIAD concept in terms of quality and reproducibility. In this contribution results on the electron energy distribution function (EEDF) and local emission of argon neutral and ion species in the plasma plume are presented. The interpretation of emission is supported by collisional radiative modeling. Main findings are the occurrence of a nonlocal EEDF and an inhomogeneous distribution of emission which is sensitive to the conditioning of the APS, like the cathode temperature. This detailed view allows a novel approach to monitor the plasma state in this particular deposition environment along with employing a control scheme for PIAD. First results obtained for oxide layers (TiO_2, Al_2O_3) are discussed.

*Funded by the German Ministry for Education and Research (BMBF, Fkz. 13N10462).

9:30
SF2 4 Plasma chemistry and scaling parameter in high-current dielectric barrier discharges used for plasma-enhanced CVD of SiO_2 on polymers R. ENGELN, S. WELZEL, *Eindhoven University of Technology, Eindhoven, The Netherlands* S.A. STAROSTIN, H. DE VRIES, *FUJIFILM Manufacturing Europe B.V., Tilburg, The Netherlands* M.C.M. VAN DE SANDEN, *Dutch Institute for Fundamental Energy Research, Nieuwegein, The Netherlands* Plasma-enhanced roll-to-roll processing of polymeric substrates in diffusive, air-like dielectric barrier discharges containing organo-silicon precursors has been shown to yield high-quality SiO_2 thin films. To scrutinise the link between the comlex precursor chemistry and the film formation complementary studies of (i) the discharge evolution, (ii) the gas phase composition, and (iii) the film properties of the silica-like films were carried out. Spatially and time-resolved optical emission provided details about the evolution of the ionisation waves in the discharge. Ex-situ Fourier-transform infrared (IR) absorption spectroscopy (AS) was implemented to study the gas phase downstream as function of injected power and hence the level of precursor consumption. Additionally, time-resolved in-situ IR laser AS was used to assess specifically the decomposition of HMDSO and TEOS. The results were corroborated by XPS and SE analysis of the layers deposited. Typically, a H-N-O chemistry in the presence of traces of hydrocarbons is observed. It transpires that the CO gas phase density is closely linked with the growth rate and the carbon content of the SiO_2 films. More importantly, the trends observed can be described by a scaling parameter.

9:45
SF2 5 Atmospheric inductively coupled Ar/H_2 plasmas jet for low-temperature deposition of Cu Thin Film on Polyimide PENG ZHAO, *Shizuoka University* WEI ZHENG, *Research and Technology Center, Yazaki Corp.* YUEDONG MENG, *Institute of Plasma Physics, Chinese Academy of Sciences* MASAAKI NAGATSU, *Shizuoka University* For fabrication of future flexible electronic devices and depositing Cu thin films on polyimide substrate at low temperature, an atmospheric inductively coupled plasma jet driven by a 13.56 MHz radio frequency (RF) power is developed. In previous studies, we found that by adding a fractional amount of H_2 gas into Ar plasma, quality of Cu film was significantly improved. But under air atmosphere, the oxidization of deposited film is inevitable. So we developed the technology in nitrogen atmosphere. We invested the plasma jet properties of Ar plasma in air, Ar/ H_2 plasma in air and Ar/ H_2 plasma in nitrogen atmosphere, to discuss the effect of adding H_2 to Ar plasma and nitrogen background on plasma properties. The plasma gas temperature diagnoses and chemical reaction research during deposition were performed by OES. The plasma jet non-equilibrium numeral simulations were also carried out for thermal and transport properties during deposition. The effects on Cu films quality were studied by means of XPS and SEM. All the plasma properties and the results of Cu film would give us an insight on the mechanism and the possibility of improving the process.

SESSION SF3: BIOMEDICAL APPLICATIONS II
Friday Morning, 4 October 2013
Room: Nassau Room at 8:30
Gregory Fridman, Drexel University, presiding

Contributed Papers

8:30
SF3 1 Controlling Reactive Oxygen and Nitrogen Species (RONS) Production by Atmospheric Pressure Plasma Jets Using Gas Shields* SETH NORBERG, *University of Michigan* ANSGAR SCHMIDT-BLEKER, JORN WINTER, STEPHAN REUTER, *ZIK Plasmatis-INP Greifswald* ERIC JOHNSEN, MARK J. KUSHNER, *University of Michigan* Atmospheric pressure plasma jets are a source of reactive oxygen and nitrogen species (RONS) for many applications, including plasma medicine. A current challenge is to deliver RONS to surfaces in a controllable manner. One such control strategy is using gas shields around the plasma jet to minimize the generation of less desired RONS by preventing ambient gases from interacting with the plasma jet effluent. In this paper, we report on results of a computational investigation of the production of RONS from plasma jets into ambient air consisting of helium seeded with either N_2 or O_2 surrounded by a flowing gas shield and the flux of those species to a treated surface. The model used in this study, *nonPDPSIM*, solves transport equations for charged and neutral species, Poisson's equation, the electron energy equation for the electron temperature, and Navier-Stokes equations for the neutral gas flow. The shield gas has significant effects on unwanted RONS in the effluent of the plasma jet. N_2 shield gas will minimize hydroxide and other reactive oxygen species in the effluent and to the surface. Similarly, O_2 shield gas can reduce the production of nitric oxide and prevent the formation of other nitrogen compounds on the surface. Comparisons will be made to experimental measurements of optical emission from plasma jets using gas shields.

*Work supported by DOE Fusion Energy Science, NSF, BMBF.

8:45

SF3 2 Plasma polymerization of 2-chloro-p-xylene to produce a crystalline plasma parylene C film* ISABEL C. ESTRADA-RAYGOZA, *IBM* STEPHAN L. THAMBAN, LAWRENCE OVERZET, MATTHEW GOECKNER, *The University of Texas at Dallas* The following work reports the study of the plasma polymerization of 2-chloro-p-xylene monomer to produce a plasma polymer film like Parylene C, a biocompatible polymer widely used in the medical field. This is the first example of a plasma polymer that presents a degree of crystallinity. Our data suggests that the film growth/polymerization of plasma deposited Parylene C is affected by both the adsorption of the monomer in the surface and the generation of precursors for polymerization by the plasma. Film deposition occurred mostly in areas exposed to ion bombardment, thus polymerization of the films is likely to be enhanced by ions but we cannot discard some small radical contribution. We used Fourier transform infrared spectroscopy, optical emission spectroscopy (OES) and an electron beam OES diagnostic tools to study the dissociation, excitation and ionization fragments produced in the plasma discharge. The main products of the monomer breakup are HCl, CH4, C2H2, H, H2, Cl, Cl2, CH, HCl+ and a mix of aromatic ions/radicals. By using a novel OES e-beam diagnostic we could track real time changes in the OES intensities of the excited species being produced and consumed in the plasma.

*This work was supported by CONACYT-UT Dallas scholarship 303255 and NSF Grant CBET- 0922962.

9:00

SF3 3 Reactive Species Processes in Plasma-, Gas-, and Liquid-Phase* STEPHAN REUTER, JOERN WINTER, MALTE HAMMER, ANSGAR SCHMIDT-BLEKER, SYLVAIN ISENI, HELENA TRESP, MARIO DÜNNBIER, KAI MASUR, KRISTIAN WENDE, *ZIK plasmatis at the INP Greifswald* KLAUS-DIETER WELTMANN, *INP Greifswald* Especially for the field of plasma medicine, plasmas interacting with liquids are of great interest for environmental, chemical, and biomedical applications. In this work we present optical diagnostics on atmospheric pressure plasma jets interacting with liquids. Combining the diagnostic results with numerical simulations yields an understanding of fundamental processes such as air species diffusion into the jet effluents or the influence on humidity. Especially for plasma treatment of physiological liquids in ambient air, atmospheric species play a key role. To achieve a desired reactive component output, the generation processes from these ambient air species are controlled. Plasma jets are characterized by planar laser induced fluorescence spectroscopy, by absorption and emission spectroscopy, and by flow simulations. With the gained knowledge we are able to tailor the reactive component composition and to influence plasma jet-liquid interaction. We show that reactive species generation within plasma treated liquid can be tuned and apply the findings to biological cells to investigate the effect of reactive oxygen and nitrogen species (RONS). The plasma treated liquids are investigated regarding their pH value, OH radicals, nitrate and nitrite, and H2O2 content. From the tailored plasma treatment a significant insight into the relevant transport processes in plasma treatment of liquids has been gained.

*Support by the German BMBF 03Z2DN11&12 is acknowledged.

9:15

SF3 4 Controlling the Effluent Chemistry of a CAP jet for Biomedical Applications: FTIR Diagnostics and Gas Phase Modeling* ANSGAR SCHMIDT-BLEKER, JOERN WINTER, SYLVAIN ISENI, MARIO DUENNBIER, ANNEMARIE BARTON, LENA BUNDSCHERER, KRISTIAN WENDE, KAI MA-

SUR, KLAUS-DIETER WELTMANN, STEPHAN REUTER, *ZIK plasmatis at the INP Greifswald e.V.* The use of cold atmospheric pressure plasma (CAP) jets with shielding gas devices has proven to be a valuable tool for biomedical applications of plasmas. In order to understand which active components generated by the plasma source trigger desired biological effects, a deeper insight into the species output of CAP jets is necessary. In this work we investigate the effect of different shielding gas compositions using a CAP jet (kinpen) operated with argon. As shielding gas various mixtures of N2 and O2 are used with relative humidity ranging from 0 to 100%. For all conditions the densities of O3, NO2, HNO3, N2O5 and N2O in the far-field of the jet are determined using Fourier-Transformed Infrared Spectroscopy (FTIR). A kinetic model for the neutral species humid air chemistry is fitted to the experimental data. The model yields insight into the processes in the CAP jets effluent. It is used to extrapolate the measured data to 2D density maps for each species depending on the O2/(O2+N2) ratio and the relative humidity. The 2D maps serve as a basis for the design of further biological and physical experiments.

*The authors gratefully acknowledge the funding by the German Ministry of Education and Research (BMBF, grant number 03Z2DN11/12).

9:30

SF3 5 Measurement of O and OH radical produced by an atmospheric-pressure helium plasma jet nearby rat skin* SEIYA YONEMORI, RYO ONO, *The University of Tokyo* Atmospheric-pressure helium plasma jet is getting much attention because it enables many kinds of plasma applications including biomedical application such as sterilization and cancer treatment. In biomedical plasma applications, it is though that active species like ions and radicals play important role. Especially, OH radical and O atom is very chemically reactive that they are deemed as major factors in cancer treatment. In this study, O and OH density distribution and its temporal behavior nearby rat skin were measured to demonstrate actual application. Plasma discharge was under AC10 kVp-p, 10 kHz with 1.5 slm (standard litter per minute) of helium gas flow. OH density was around 1 ppm and O atom density was around 10 ppm at maximum. We also measured time-evolution of OH and O atom density. Both OH and O density was almost constant between discharge pulses because lifetime of active species could be prolonged in helium. And density distribution of both species varied depending on helium flow rate and water concentration on the surface; on rat skin or on the grass surface. Those results suggest the production mechanisms and provision mechanisms of O atom and OH radical by an atmospheric-pressure helium plasma jet.

*This work is partially supported by the Grant-in-Aid for Science Research by the Ministry of Education, Culture, Sport, Science and Technology.

9:45

SF3 6 Plasma-polymerized methyl methacrylate via intense and highly energetic atmospheric pressure micro-plasma for biomedical applications CHOON-SANG PARK, JOHN BALLATO, SUNG-O KIM, *Center for Optical Materials Science and Engineering Technologies, Clemson University* CLEMSON UNIVERSITY TEAM Poly (methyl methacrylate), PMMA, has been widely used as a biocompatible material in bone cement, dental fillings, and many other bio-related applications. Vacuum plasmas and radio frequency (RF) atmospheric plasmas are the most common methods for depositing plasma-derived thin films and nanoparticles. However, the necessary equipment is difficult to operate and maintain

as well as being large and expensive. Here, we report the use of a novel intense and highly energetic atmospheric pressure plasma jet array using direct plasma jet-to-jet coupling effects to deposit high quality plasma-polymerized MMA (PPMMA) for bio-medical applications. The newly proposed atmospheric pressure micro-plasma jet array device can generate the intense plasma mode with a strong plasma emission and high plasma particle energy. PPMMA was successfully deposited on a variety of substrates and characterized by SEM, AFM, and FT-IR. The micro-plasma jet is obtained at a sinusoidal voltage with a peak value of 30 kV and frequency of 35 kHz. Argon gas was employed as the discharge gas for plasma generation and its flow rate was in the range of 2230 sccm, Methyl methacrylate (MMA) monomer was vaporized by means of a glass bubbler which was supplied by argon gas with flow rates in the range of 268 sccm from room temperature to $400°C$. The deposited PPMMA thin films were flexible, transparent, thin, and strong on metal substrates.

SESSION SF5: ELECTRON COLLISIONS WITH ATOMS AND MOLECULES II
Friday Morning, 4 October 2013; Room: Village Square at 8:30; Michael Brunger, Flinders University, presiding

Invited Papers

8:30
SF5 1 Imaging of the dissociation dynamics of polyatomic molecules following low-energy electron resonant attachment*
ALI BELKACEM, *Lawrence Berkeley National Laboratory*

We will present a study that combines experimental data along with theoretical analysis of dissociative electron attachment to carbon dioxide, methanol and uracil. In these studies we demonstrated that an understanding of anion dissociation dynamics beyond simple one-dimensional models is crucial in interpreting the measured angular distributions. Although, for example, several possible dissociation mechanisms involving conical intersections have been identified for the lowest resonance and discussed in the case of CO_2, the most likely scenario points to an initial linear asymmetric stretch motion to geometries where the autodetachment probability is small, followed by bending motion around a conical intersection. We also investigated the dynamics of DEA to methanol for the low-energy Feshbach resonance at 6.5 eV. The angular distributions of the recoiling fragments were found to deviate significantly from the axial recoil approximation that was used previously to accurately describe the dynamics in the analogous 2B1 resonance in water. Observation of the dynamics of dissociative electron attachment (DEA) in biomolecules has recently become possible by momentum imaging of the fragments. Guided by electronic structure and scattering we observed key aspects of the dynamics of ring-breaking dissociation of the transient anion formed upon DEA to the nucleobase uracil.

Contributed Papers

9:00
SF5 2 Comprehensive Study of 3-Body and 4-Body Models of Single Ionization of Helium* ALLISON HARRIS, *Illinois State University* KAYLA MORRISON, *University of Arkansas* For decades the frozen core approximation has been successfully used to model 4-Body collisions as 3-Body processes. In recent years, full 4-Body models have been used to calculate fully differential cross sections (FDCS) for single ionization of helium, and these 4-Body models show discrepancies with the 3-Body models. We have identified four possible sources of the discrepancies, which are: the initial state helium wave function, the final state He^+ wave function, the final state potential for the outgoing electrons, and the perturbation. To identify which of these four sources causes in the differences in FDCS, we have performed a comprehensive study of 3-body and 4-body models for a wide range of incident projectile energies, ionized electron energies, and scattering angles.

9:15
SF5 3 Accurate calculations of the relativistic rise in electron-impact excitation cross sections for highly charged ions*

CHRISTOPHER J. BOSTOCK, DMITRY V. FURSA, IGOR BRAY, *Curtin University* CHRISTOPHER J. FONTES, HONG LIN ZHANG, *Los Alamos National Laboratory* Exact relativistic plane-wave Born (RPWB) matrix elements of the Møller interaction are incorporated in the "analytic Born subtraction technique" and employed in the Relativistic Convergent Close-Coupling (RCCC) method. Application to the calculation of high-energy electron-impact excitation cross sections of highly charged hydrogenlike ions demonstrates the "Bethe rise", an effect that is manifest in Bethe's original 1932 work [1] on relativistic high-energy, electron-impact excitation. The result represents an improvement over Bethe's relativistic high-energy theory developed in the 1930's in that (i) both target and projectile electrons are represented relativistically with Dirac spinor wavefunctions and (ii) the dipole approximation plus additional assumptions are not employed in the RPWB scattering amplitude of the Møller interaction. We show that as the Z of the target increases, the onset of the rise occurs at lower, absolute projectile energies. The onset occurs at significantly lower energies, when expressed in threshold units, as Z increases, which could have important consequences for the collisional-radiative modeling of high-Z plasmas.

[1]H. Bethe, Z. Phys. **76**, 293 (1932).

9:30

SF5 4 Sturmian approach to the study of photoionization of atoms and molecules CARLOS MARIO GRANADOS CASTRO, LORENZO UGO ANCARANI, *Universite de Lorraine, France* GUSTAVO GASANEO, *Universidad Nacional del Sur, Argentina* DARIO M. MITNIK, *IAFE, Buenos Aires, Argentina* In this presentation we study the photoionization of atoms and molecules using ultrashort laser pulses, solving the time-independent Schrödinger equation (TISE) in a first order perturbation theory. The interaction laser-matter is described with the dipolar operator in the velocity gauge. Generalized Sturmian functions [1] are used to solve the driven equation for a scattering wave function which includes all the information about the ionization problem. For the atomic case, we study the photoionization of He atom using the Hermann-Skillman potential together with the one-active electron approximation. For molecular systems (CH_4 in this work), we use first a spherically symmetric potential $U_i(r)$ [2], and then a more realistic potential that includes all the nuclei and other electrons interaction, as in [2]. For each molecular orbital we use Moccia's wave functions [3], solve the TISE with an initial molecular orbital i of the ground state and extract the corresponding photoionization cross sections. For both atomic and molecular systems we compare our results with previous calculations and available experimental data.

[1] D. M. Mitnik *et al.*, Comp. Phys. Comm. **182**, 1145 (2011); Gasaneo *et al.*, submitted to Adv. Quantum Chem (2013).
[2] L Fernandez-Menchero and S Otranto, Phys. Rev. A **82** 022712 (2010).
[3] R. Moccia, J. Chem. Phys. **40** 2164 (1964).

SESSION TF1: DIAGNOSTICS II
Friday Morning, 4 October 2013
Room: Ballroom I at 10:30
Azer Yalin, Colorado State University, presiding

Contributed Papers

10:30

TF1 1 Time-resolved in-situ quantum cascade laser absorption spectroscopy in dielectric barrier discharges S. WELZEL, F. BREHMER, *Eindhoven University of Technology, Eindhoven, The Netherlands* M.C.M. VAN DE SANDEN, *Dutch Institute for Fundamental Energy Research (DIFFER), Nieuwegein, The Netherlands* R. ENGELN, *Eindhoven University of Technology, Eind-* hoven, *The Netherlands* Modern mid-infrared laser sources, known as quantum cascade lasers (QCLs), provide a means for highly time-resolved absorption spectroscopy in the molecular "fingerprint" region. Pulsed distributed feedback QCLs are especially suited for diagnostic studies on transient plasmas as the time-resolution can be as good as a few tens of nanoseconds. Dielectric barrier discharges in CO_2 operated in the mid-frequency (kHz) range were studied by means of in-situ QCL absorption spectroscopy in single and multiple-pass configuration. Different synchronisation schemes were applied to achieve phase-resolved measurements during individual AC cycles as well as to monitor molecular absorption signals during pulsed operation. Mixing ratios of CO in its electronic and vibrational ground state were of the order of a few percent and thus confirmed ex-situ studies of the effluent. Interestingly, the concentrations levels were changing only slowly in time, i.e. of the order of the residence time. A direct CO_2-to-CO dissociation through electron impact appears very unlikely under these conditions. The kinetics of low-lying ro-vibrational states of CO_2 along with the evolution of the CO concentration were measured on a sub-millisecond time-scale to establish the (rotational) gas temperatures.

10:45

TF1 2 Analytical Study of the Curling Probe: Resonance Frequencies ALI ARSHADI, RALF PETER BRINKMANN, *Department for Electrical Engineering and Information Sciences, Ruhr University Bochum* The term "active resonance spectroscopy" refers to a class of plasma diagnostic techniques which utilizes the ability of plasmas to resonate on or near to the electron plasma frequency. The curling probe is a newly developed variant which may be called an optimized (in particular: miniaturized)hair pin probe [1, 2]. The device can be mounted coplanar in the discharge chamber wall where it practically causes no perturbation of the plasma. Like the hair pin probe, it is resonant with a frequency f_0 under vacuum conditions, but experiences a frequency shift in the presence of plasma. However, no reliable analysis exists which relates the magnitude of this shift to the absolute value of the plasma density. In this contribution, we will fill this gap. We first derive a formula for the phase velocity of an electromagnetic wave which propagates along a slit in a thin, perfectly conducting screen located between to dielectrics, and then show how this result can be used to describe the resonance frequencies of the curling probe.

[1] R. B. Piejak *et al.*: J. Appl. Phys. **95** (2004) 3785.
[2] I. Liang *et al.*: Appl. Phys. Express **4** (2011) 066101.

Invited Papers

11:00

TF1 3 Quantitative diagnostics of reactive, multicomponent low-temperature plasmas* THOMAS SCHWARZ-SELINGER, *Max-Planck Institut für Plasmaphysik, EURATOM Association, Germany*

The special emphasis in this work is put on the quantitative determination of the plasma composition of an inductively coupled low temperature plasma (ICP). Several standard plasma diagnostic techniques were applied. As a test case for a multi-component low-temperature plasma argon-hydrogen as well as argon-hydrogen-nitrogen mixed plasmas were investigated. For steady-state plasma operation the ion density and electron temperature were determined with a single tip Langmuir probe. A multi-grid miniature retarding-field analyzer was used to measure the mass integrated ion flux. An energy-dispersive mass spectrometer - a so-called plasma monitor (PM) - was applied to sample ions from the plasma to derive the ion composition. The degree of dissociation of hydrogen and the gas temperature were derived from optical emission spectroscopy. The gas temperature was estimated by the rotational distribution of the Q-branch lines of the hydrogen Fulcher-α diagonal band for the argon-hydrogen mixed plasmas and from the second positive system of N_2 in argon-hydrogen-nitrogen mixed plasmas. The degree of dissociation of hydrogen was measured by actinometry. The influence of the substrate material of the counter electrode (stainless steel, copper, tungsten, Macor, and aluminium) on the atomic hydrogen concentration was investigated by OES. In addition, ionization-threshold mass spectrometry (ITMS)

was used to determine the densities of atomic nitrogen (N) and atomic hydrogen (H and D). Pulsed plasma operation was applied to directly measure the loss rate of H, D and N in the afterglow from the temporal decay of the ITMS signal. From these data the wall loss probability of atomic hydrogen was determined. Furthermore, a zero-dimensional rate equation model was devised to explain the ion composition in these mixed plasmas with different admixture ratios. In addition to the experimental data on electron density, gas temperature, total pressure, atomic hydrogen density, and Ar, H_2, and N_2 fraction, the chamber geometry and the required collisional rate coefficients are input parameters for the model. The model was applied to calculate the ion densities and the electron temperature and describes the main features reasonably well supporting the validity of the plasma diagnostics applied.

*In collaboration with Maik Sode and Wolfgang Jacob, Max-Planck Institut für Plasmaphysik, EURATOM Association, Germany.

Contributed Papers

11:30

TF1 4 Absolute atomic oxygen and nitrogen densities in radio-frequency driven atmospheric pressure cold plasmas: synchrotron vacuum ultra-violet high-resolution Fourier-transform absorption measurements* K. NIEMI, D. O'CONNELL, *York Plasma Institute, University of York, UK* N. DE OLIVEIRA, D. JOYEUX, L. NAHON, *Synchrotron Soleil, France* J.P. BOOTH, *Laboratoire de Physique des Plasmas-CNRS, Ecole Polytechnique, France* T. GANS,[†] *York Plasma Institute, University of York, UK* Reactive atomic species play a key role in emerging cold atmospheric pressure plasma applications, in particular in plasma medicine. Absolute densities of atomic oxygen and atomic nitrogen were measured in a radio-frequency driven nonequilibrium plasma operated at atmospheric pressure using vacuum ultra-violet (VUV) absorption spectroscopy. The experiment was conducted on the DESIRS synchrotron beamline using a unique VUV Fourier-transform spectrometer. Measurements were carried out in plasmas operated in helium with air-like N_2-O_2 (4:1) admixtures. A maximum in the O-atom concentration of $9.1 \, 10^{20}$ m^{-3} was found at admixtures of 0.35 vol%, while the N-atom concentration exhibits a maximum of $5.7 \, 10^{19}$ m^{-3} at 0.1 vol%.

*The authors acknowledge support by the UK EPSRC through the grants EP/H003797/1 and EP/K018388/1.
[†]Presenting author

11:45

TF1 5 Spatially resolved measurement of Ar excited species in magnetized inductively coupled plasma using multi-port optical emission spectroscopy* YUN-GI KIM, CHANG-SEUNG HA, MOON-KI HAN, KWON-SANG SEO, DONG-HYUN KIM, HAE JUNE LEE, HO-JUN LEE, *Department of Electrical Engineering, Pusan National University* IL GYO KOO, SOOJIN LEE, HYO-SEONG SEONG, *Research center, SEMES* Optical emission spectrometry (OES), which is the spectral analysis of the light emanating from plasma, is probably the most widely used method for monitoring and diagnosis of plasma processes. This technique has the advantage of being external to the reactor and vacuum system. However, the OES method is limited to measure spatial distribution of species accurately. In this work, multi-port optical emission spectroscopy system was developed to improve the space-resolved ability. This multi-port OES system consists of Si wafers, optical fibers, prisms and windows. The Si wafers are used for making the same condition while this device is put in the etching or deposition reactor. The emission light from plasma is collected and transferred through the optical fibers. The spatial distribution of Ar excited species is measured using this device in inductively coupled plasma with and without external axial magnetic field. The off-axis density profile of electron, Ar ion and excited species are appeared in weakly magnetized inductively coupled plasma. Also the emission intensity was changed in this experimental condition. Two-dimensional simulation was studied to verify this experimental result.

*This was supported by SEMES cooperative research project.

12:00

TF1 6 Polymerizable Supramolecular Sensor for Plasma Diagnostics on Wafer Level HYO-CHANG LEE, *Department of Electrical Engineering, Hanyang University, Seoul 133-791, Korea* SEONG-HO JEON, JONG-MAN KIM, *Department of Chemical Engineering, Hanyang University, Seoul 133-791, Korea.* CHIN-WOOK CHUNG, *Department of Electrical Engineering, Hanyang University, Seoul 133-791, Korea* Low temperature reactive plasma allows fabrication of high quality nano-device owing to the synergy effect of the plasma, especially ions impinging on the wafer. We have developed a large area wafer-type plasma diagnostic system based on the polymerizable supramolecular sensor (PSS) that affords colorimetric and fluorometric monitoring of spatial ion density distribution. The PSS system does not require electric circuits or batteries and is found to be very sensitive to the plasma and allows efficient mapping of the ion density distribution. The readily available and conceptually new method should find great utility in the field of plasma diagnostics.

SESSION TF2: LOW PRESSURE PLASMA MODELING II
Friday Morning, 4 October 2013; Room: Ballroom II at 10:30; Mirko Vukovic, Tokyo Electron, presiding

Invited Papers

10:30

TF2 1 Verification and Validation in Low Temperature Plasma Physics
MILES TURNER, *Dublin City University*

Plasma simulation is a widely used tool, for reasons ranging from clarification of basic scientific questions to engineering design studies. Clearly, activities such as these are valuable only if the simulations are correct, in some relevant sense.

Indeed, it is not enough for the simulations to be correct. Evidence that the simulations are correct needs to be available to the community interested in the simulation results. In recent years, these issues have come to seem problematic, in part because of evidence that common practice is ineffective in detecting faulty simulations. Broadly speaking, two kinds of faults in simulations can be distinguished: (1) Incorrect or inappropriate physical models, including inaccurate choices of parameters, and (2) incorrect implementation of the physical model in software. Two kinds of tests are therefore needed to establish that a simulation is fit for purpose: Tests of software correctness, known as verification, and tests of model correctness, known as validation. Verification is a formal activity; Validation involves reference to experiments. This paper will discuss recent progress on application of these concepts in low-temperature plasma physics, with more emphasis on verification than on validation.

11:00

TF2 2 Towards adaptive kinetic-fluid simulations of low-temperature plasmas*
VLADIMIR KOLOBOV, *CFD Research Corporation*

The emergence of new types of gaseous electronics in multi-phase systems calls for computational tools with adaptive kinetic-fluid simulation capabilities. We will present an Adaptive Mesh and Algorithm Refinement (AMAR) methodology for multi-scale simulations of gas flows and discuss current efforts towards extending this methodology for weakly ionized plasmas. The AMAR method combines Adaptive Mesh Refinement (AMR) with automatic selection of kinetic or fluid solvers in different parts of computational domains. This AMAR methodology was implemented in our Unified Flow Solver (UFS) for mixed rarefied and continuum flows. UFS uses discrete velocity method for solving Boltzmann kinetic equation under rarefied flow conditions coupled to fluid (Navier-Stokes) solvers for continuum flow regimes. The main challenge of extending AMAR to plasmas comes from the distinction of electron and atom mass. We will present multi-fluid, two-temperature plasma models with AMR capabilities for simulations of glow, corona, and streamer discharges. We will briefly discuss specifics of electron kinetics in collisional plasmas, and deterministic methods of solving kinetic equations for different electron groups. Kinetic solvers with Adaptive Mesh in Phase Space (AMPS) will be introduced to solve Boltzmann equation for electrons in the presence of electric fields, elastic and inelastic collisions with atoms. These kinetic and fluid models are currently being incorporated into AMAR methodology for multi-scale simulations of low-temperature plasmas in multi-phase systems.

*Supported by AFOSR, NASA, and DoE

Contributed Papers

11:30

TF2 3 Two-dimensional extended fluid model for a dc glow discharge with nonlocal ionization source term* ISMAIL RAFA-TOV, *Middle East Technical University, Ankara, Turkey* EUGENY BOGDANOV, ANATOLIY KUDRYAVTSEV, *Saint Petersburg State University, St. Petersburg, Russia* Numerical techniques applied to the gas discharge plasma modelling are generally grouped into fluid and kinetic (particle) methods, and their combinations which lead to the hybrid models. Hybrid models usually employ Monte Carlo method to simulate fast electron dynamics, while slow plasma species are described as fluids. However, since fast electrons contribution to these models is limited to deriving the ionization rate distribution, their effect can be expressed by the analytical approximation of the ionization source function, and then integrating it into the fluid model. In the context of this approach, we incorporated effect of fast electrons into the "extended fluid model" of glow discharge, using two spatial dimensions. Slow electrons, ions and excited neutral species are described by the fluid plasma equations. Slow electron transport (diffusion and mobility) coefficients as well as electron induced reaction rates are determined from the solutions of the electron Boltzmann equation. The self-consistent electric field is calculated using the Poisson equation. We carried out test calculations for the discharge in argon gas. Comparison with the experimental data as well as with the hybrid model results exhibits good applicability of the proposed model.

*The work was supported by the joint research grant from the Scientific and Technical Research Council of Turkey (TUBITAK) 212T164 and Russian Foundation for Basic Research (RFBR).

11:45

TF2 4 Self-Consistent Simulations of the Radial Line Slot Antenna Plasma Source PETER VENTZEK, *Tokyo Electron America* ROCHAN UPADHYAY, *Esgee Technologies Inc.* MICHITAKA AITA, JUN YOSHIKAWA, TOSHIHIKO IWAO, KIYOTAKA ISHIBASHI, *Tokyo Electron Ltd.* LAXMINARAYAN RAJA, *The University of Texas at Austin* The radial line slot antenna plasma source couples microwave power through a slot antenna structure and window to a plasma characterized by a generation zone adjacent to the window and a diffusion zone that contacts a substrate. The diffusion zone is characterized by a very low electron temperature. This property renders the source useful for soft etch applications and thin film processing for which low ion energy is desirable. The transport of electrons from the point of generation through the diffusion is characterized by a relaxing electron energy distribution function. The transport is difficult to describe using a quasi-neutral model and a zero dimensional solution of Boltzmann's Equation. A hybrid approach in which test particle electrons are used to describe the electron kinetics is demonstrated. The impact of driving frequency, metastable pooling on the spatial distribution of the electron energy distribution function will be described for argon plasmas.

12:00

TF2 5 Numerical Approaches for the Optimization of Plasma Sources for Space Thrusters DAVIDE MELAZZI, *CISAS "G. Colombo," University of Padova, Italy* VITO LANCELLOTTI, *Eindhoven University of Technology, Eindhoven, The Netherlands* ALESSANDRO CARDINALI, *Associazione Euratom-ENEA sulla Fusione, Frascati, Rome, Italy* MARCO MANENTE, *hit09 S.r.l., Padova, Italy* DANIELE PAVARIN, *University of Padova, Italy* The optimization of radiofrequency magnetized plasma sources for space thrusters has focused on power deposition in nonuniform

plasmas. However, many researchers assumed rather than computed the induced current density on the antenna, and considered a uniform and constant magneto-static field aligned with the source axis. To overcome these limitations, we propose two methods: (i) a full-wave approach to compute the current distribution on the antenna and (ii) a ray-tracing approach to investigate the influence of actual magneto-static fields on the wave propagation and power deposition. Plasma density profiles are included in both approaches. In the full-wave method, we derive a surface integral equation for the antenna and a volume integral equation for the plasma by applying the electromagnetic equivalence principles. A comparative study of different antennas will be presented. In the second method, the propagation and absorption of electromagnetic waves are investigated by solving the 3D Maxwell-Vlasov model equations by a WKB asymptotic expansion. Unconventional mode conversions and power deposition profiles are found when realistic confinement magnetic field are considered.

SESSION TF3: THERMAL PLASMAS, NEGATIVE ION PLASMAS, AND DUSTY PLASMAS
Friday Morning, 4 October 2013
Room: Nassau Room at 10:30
Brooke Stutzman, U.S. Coast Guard Academy, presiding

Contributed Papers

10:30

TF3 1 Calculation of thermodynamic and transport properties of thermal plasmas based on the Cantera software toolkit CHARLES DOIRON, KAI HENCKEN, *ABB Switzerland LTD, Corporate Research* Computational fluid-dynamic simulations nowadays play a central role in the development of new gas circuit breakers. For these simulations to be reliable, a good knowledge of the pressure and temperature-dependence of the thermodynamic and transport properties of ionized gases is required. A key ingredient in the calculation of thermodynamic properties of thermal plasmas is the calculation of the chemical equilibrium composition of the gas. The general-purpose, open-source software toolkit Cantera provides most functionality required to carry out such thermodynamic calculations. In this contribution, we explain how we tailored Cantera specifically to calculate material properties of plasmas. The highly modular architecture of this framework made it possible to add support for Debye-Hückel non-ideality corrections in the calculation of the chemical equilibrium mixture, as well as to enable the calculation of the key transport parameters needed in CFD-based electric arc simulations: electrical and thermal conductivity, viscosity, and diffusion coefficients. As an example, we discuss the thermodynamic and transport properties of mixtures of carbon dioxide and copper vapor.

10:45

TF3 2 Simultaneous measurements of OH(A) and OH(X) radicals in microwave argon plasma assisted combustion of methane/air mixtures using optical emission spectroscopy and cavity ringdown spectroscopy* WEI WU, CHUJI WANG, *Mississippi State University* LASER SPECTROSCOPY AND PLASMA TEAM We developed a new plasma assisted combustion system employing a continuous atmospheric argon microwave plasma jet to enhance combustion of methane/air mixtures in different fuel equivalence ratios (φ). The combustor has three distinct reaction zones of pure plasma zone, the hybrid plasma-flame zone and pure flame zone which were well defined by their emission spectra.

Optical emission spectroscopy (OES) was used to exam the excited species including OH(A) and results showed that OH(A) intensities gradually increased in plasma zone and rapidly increased in hybrid zone and then dramatically decreased to a very low level in flame zone. In addition to OES, pulsed cavity ringdown spectroscopy (CRDS) was utilized to measure the absolute number density of OH(X) in the flame zone at $\varphi = 0.51$, 0.87, 1.10 and 1.45. Different OH(X) number densities and density profiles were observed comparing rich and lean combustions. At $\varphi = 0.51$, the OH(X, V'' = 0, J'' = 0.5) number density increased from 2.29×10^{15} molecule cm^{-3} at the combustor nozzle to maximum 3.13×10^5 molecule cm^{-3} at 2 mm downstream, and then gradually decreased to the lowest detectable level of 0.12×10^{15} molecule cm^{-3} in the far downstream.

11:00

TF3 3 Erosion of thermionic cathodes VALERIAN NEMCHINSKY, *None* Two types of the thermionic cathodes are used in industry: a) Tungsten (doped with thoria or pure) cathodes burning in a unreactive gas, and b) Thermo-chemical cathodes, such as a Hafnium cathode burning in oxygen plasma gas (mostly used plasma cutting). Both types of the cathodes experience cycle (arc on/off) erosion and constant current erosion. Available experimental data for both types of cathodes and both types of erosions (constant current and cycling) are presented and discussed. Based on the model [1,2] the constant current erosion rate is calculated. Comparison of the results of the calculations with the experimental data show reasonable agreement. Existing hypotheses on cycling erosion are also discussed. For the Tungsten cathode, it is suggested that the start erosion is mainly due to the cold cathode mode (vacuum arc mode) of the arc operation that takes place just after the arc ignition. The presented estimation doesn't contradict this hypothesis. For the Hafnium cathode, the model of the "open can" erosion [3] is supported by recently published observations.

[1]V. A. Nemchinsky J. Phys. D **45**, 135201.
[2]V. A. Nemchinsky Plasma Chem.Plasma Proces. **33**, 517.
[3]V. A. Nemchinsky J. Phys. D **36**, 1573.

11:15

TF3 4 The Effect of Single Particle Charge Limits on Particle Charge Distributions in Dusty Plasmas* STEVEN GIRSHICK, ROMAIN LE PICARD, *Dept. of Mechanical Engineering, University of Minnesota, Minneapolis, MN* There is a limit to the number of electrons that can coexist on a dust particle in a plasma. This limit depends on the particle's surface potential, electron affinity and the inter-electron Coulomb repulsion. We conducted numerical simulations that examine the effect of charge limits on steady-state particle charge distributions, as well as on the time required to reach steady state. Attachment of electrons to a cloud of nanoparticles can severely deplete the electron density and increase the ion density, causing the electron-to-ion density ratio to be much less than unity. At sufficiently high values of the density ratio, e.g. above about 0.1 for 80-nm-diameter Si particles, the charge limit strongly constrains particle charge. At lower values of the density ratio, e.g. around 0.01, particles are much less negatively charged even in the absence of a charge limit, and therefore the limit makes only a small difference. However, in this regime the charge distribution still deviates from the Gaussian form predicted by previous work that neglects charge limits. For the case of Maxwellian electron velocity distributions, we find that whether or not particle charge distributions are significantly affected by charge limits depends on the dimensionless asymmetry charging factor p and on particle

size. The factor p in turn depends on the ratios of electron-to-ion density, temperature and mass.

11:30
TF3 5 Plasma physical and plasma chemical aspects of nanoparticle formation in hydrocarbon plasmas JOHANNES BERNDT, EVA KOVACEVIC, *GREMI, University of Orleans, France* ILIJA STEFANOVIC, *Institut of Physics, Belgrade, Serbia* Low temperature plasmas are a breeding place for a great variety of different species, that can be used for different applications as the deposition of thin films or the the synthesis of nanoparticles and nanocomposites. However the distinctive nonequilibrium character of theses plasmas makes their understanding and their control a rather challenging task. The solution of this task is in addition hampered by the fact that decisive factors like cross sections for electron impact processes or rate coefficients for molecule-molecule reactions are very often completely unknown. In particular reactions including the walls of the plasma reactor are difficult to account for since they depend on the nature of the involved molecules and on the nature of the wall itself. This contribution deals with two simple approaches to control plasma chemical processes in a reactive low temperature plama: the variation of the diffusion length and the pulsing of the discharge. The contribution will focus on experiments performed in rf low pressure hydrocarbon plasmas with special emphasis on the influence of plasma physical and plasma chemical processes on the formation and properties of nanoparticles.

11:45
TF3 6 Controlling Plasma Channels through Ultrashort Laser Pulse Filamentation* ANDREY IONIN, LEONID SELEZNEV, *Lebedev Physical Institute of the Russian Academy of Sciences* ELENA SUNCHUGASHEVA, *Lebedev Physical Institute of the Russian Academy of Sciences; Moscow Institute of Physics and Technology* A review of studies fulfilled at the Lebedev Institute in collaboration with the Moscow State University and Institute of Atmospheric Optics in Tomsk on influence of various characteristics of ultrashort laser pulse on plasma channels formed under its filamentation is presented. Filamentation of high-power laser pulses with wavefront controlled by a deformable mirror, with cross-sections spatially formed by various diaphragms and with different wavelengths was experimentally and numerically studied. An application of plasma channels formed due to filamentation of ultrashort laser pulse including a train of such pulses for triggering and guiding long electric discharges is discussed.

SESSION TF5: ELECTRON-MOLECULE COLLISIONS
Friday Morning, 4 October 2013; Room: Village Square at 10:30; Don Madison, Missouri University of Science and Technology, presiding

Invited Papers

10:30
TF5 1 The Dynamics of Dissociative Electron Attachment to Small Polyatomic Molecules*
THOMAS RESCIGNO, *Lawrence Berkeley National Laboratory*

Dissociative electron attachment (DEA) is a resonant process in which an electron attaches to a molecule to form an unstable anion which subsequently fragments into stable products. DEA to small polyatomic molecules is often governed by complex electronic and nuclear dynamics that is intrinsically multi-dimensional. One-dimensional treatments of the dissociation dynamics based on resonance scattering theory, while often successful in modeling the energy dependence of total cross sections, can mask the complexity of post-attachment dynamics which is revealed by the observed angular dependence of the reaction products. The dissociation evolves on transient anion potential energy surfaces and often involves conical intersections which can result in a complete breakdown of the axial recoil approximation. I will use the examples of DEA to water, carbon dioxide and methanol to illustrate the discussion.

Contributed Papers

11:00
TF5 2 Electron scattering from H_2^+ molecule* DMITRY V. FURSA, MARK C. ZAMMIT, JEREMY S. SAVAGE, IGOR BRAY, *Curtin University* We have extended the *ab initio* convergent close-coupling (CCC) method to electron scattering from molecules within the adiabatic approximation. As a first application of the method we consider the most fundamental molecule: molecular hydrogen ion. Experimentally H_2^+ is produced in a number vibrationally excited states (up to $\nu = 18$ in some experiments). Fixed-nuclear scattering calculations have been performed at a number internuclear distances within the CCC method formulated in both spherical and spheroidal coordinates. We have calculated potential energy curve and the required vibrational wave functions, and produced adiabatic approximation cross sections for dissociative excitation and ionisation processes. Comparison with available experimental and theoretical results will be presented.

11:15
TF5 3 Fully Differential Cross Sections for Electron-Impact ionization of aligned molecules* ESAM ALI, DON MADISON, *Missouri University of Science & Technology* JULIAN LOWER,

Institute für Kernphysik, Goethe Universität ERICH WEIGOLD, AMPL, Research School of Physics and Engineering SUSAN BELLM, ARC CoE for Antimatter - Matter Studies, Flinders University ALLISON HARRIS, Henderson State University CHUAN-GANG NING, Tsinghua University Most experiments measuring electron-impact ionization of molecules do not determine the orientation of the molecule at the time of ionization. One way to determine the orientation is to simultaneously ionize the molecule and excite the residual ion to a state that will dissociate. The orientation of the molecule can then be determined by detecting one of the dissociation fragments since the fragments will leave in the direction of orientation. We will present Fully differential cross sections for 176 eV electron-impact dissociative excitation-ionization of oriented H2. These results show a strong dependence of the dissociative ionization-exictation process on the alignment of the internuclear axis with respect to the projectile momentum and emission directions of the scattered and ejected electrons.

Invited Papers

11:30

TF5 4 Recent Theoretical Studies of Dissociative Recombination*
STEVEN GUBERMAN, *Institute for Scientific Research*

After decades of progress, quantitative agreement between theory and experiment for dissociative recombination (DR) cross sections has remained elusive. Using ab initio potential curves, widths and the MQDT approach (Guberman, 2012) the DR of N2+, i.e. N2+ $+ e^- \rightarrow N + N$, has been analyzed for each of the lowest 5 ion vibrational levels. It is shown that agreement with future high resolution experiments requires that theory account for minor dissociative routes. The cross sections and rate constants are compared to the results of afterglow and merged beam experiments. Good agreement is obtained for the v = 0 rate constant. The only storage ring experiment (CRYRING) to measure cross sections and rate constants found that two unknown ion vibrational distributions gave similar values, (Peterson *et al.*, 1998) leading to the conclusion that the rate constants must be similar for each of the lowest 4 ion vibrational levels. The theory finds that at low electron temperatures the rate coefficients are indeed similar but above room temperature the larger rate coefficient for v = 0 diverges from the others by factors of 2 − 3. The rate constant for "elastic" capture in which the electron is captured but emitted before dissociation has been calculated and allows for the determination of the fraction of collisional captures that lead to DR. For v = 0, DR results from 2 out of every 10 captures. Guberman, S. L., J. Chem. Phys. **137**, 074309 (2012); Peterson, J. R. *et al.*, J. Chem. Phys. **108**, 1978 (1998).

Contributed Papers

12:00

TF5 5 Electron and photon excitation and ionization of tetrahydrofurfuryl alcohol* MICHAEL J. BRUNGER, LUCA CHIARI, DARRYL JONES, PENNY THORN, ZOE PETTIFER, GEORGE BARBOSA DA SILVA, *CAMS, Flinders University, Adelaide, Australia* GUSTAVO GARCIA, *Instituto de Fisica Fundamental, CSIC, Madrid, Spain* FRANCISCO BLANCO, *Universidad Complutense de Madrid, Madrid, Spain* F. FERREIRA DA SILVA, P. LIMAO-VIEIRA, *Universidade Nova de Lisboa, Caparica, Portugal* M.-J. HUBIN-FRANSKIN, J. DELWICHE, *Universite de Liege, Liege, Belgium* We present differential cross section measurements for the low-energy electron-impact excitation of the electronic states of the biologically important molecule tetrahydrofurfuryl alcohol (THFA). Electron energy loss spectra have been measured at selected incident energies between 15 eV and 50 eV and for scattering angles in the 15-90 degrees range using an electron spectrometer. The absolute scale of the inelastic DCSs is set by the elastic DCSs calculated with the Independent Atom Model with Screening Corrected Additivity Rule approach between 1 and 1000 eV. We also present results from VUV photoabsorption and He(I) photoelectron spectra for THFA. A comparison between the results obtained with these different techniques is provided.

12:15

TF5 6 Electron impact total cross sections for components of DNA and RNA molecules* MINAXI VINODKUMAR, *V.P. & R.P.T.P. Science College* CHETAN LIMBACHIYA, *P.S. Science & H.D.Patel Arts College, KADI* MAYURI BAROT, AVANI BAROT, *V.P. & R.P.T.P. Science College* MOHIT SWADIA, *P.S. Science & H.D.Patel Arts College, KADI* Biomolecules, in particular DNA/RNA components are prone to high energy radiation damage which can occur due to primary, secondary or reactive processes [1]. We report electron impact total cross sections (Q_T), total elastic cross sections (Q_{el}) and total inelastic cross sections (Q_{inel}) for components of DNA and RNA molecules from threshold to 2000 eV. These components include Uracil ($C_4H_4N_2O_2$), Thymine ($C_5H_6N_2O_2$), Cytosine ($C_4H_5N_3O$), Adenine ($C_5H_5N_5$), Guanine ($C_5H_5N_5O$) and Phosphoric acid (H_3PO_4). We have employed Spherical Complex Optical Potential (SCOP) formalism [2] to calculate the total elastic cross sections, total inelastic cross sections and total cross sections.

[1] L. Sanche "Radical and Radical Ion Reactivity in Nucleic Acid Chemistry (Greenberg, M. ed.), John Wiley &. Sons, Inc. 239 (2009).
[2] Minaxi Vinodkumar and Chetan Limbachiya, Molecular Physics **111** 213(2013).

SESSION UF1: SCIENTIFIC LEGACY OF ARTHUR PHELPS
Friday Afternoon, 4 October 2013
Room: Ballroom I at 13:30
Bruce Wedding, University of South Australia, presiding

Contributed Papers

13:30

UF1 1 Important Research by Art Phelps in the 1950s J.E. LAWLER, *Univ. of Wisconsin* Art Phelps made major contributions to the field of Gaseous Electronics. This talk is a review of some of Art's most important papers from the 1950s while he was a young scientist at Bell Labs and then at Westinghouse. The earliest theories of a simple discharge plasma, a positive column, incorporated the assumption of single-step electron-impact ionization. Both the ionization and power balance of most discharges are dominated by multi-step processes. Art's early studies of helium metastable atoms [1,2] were tremendously clever applications of the experimental technology available in the 1950s. His studies laid the foundation for our modern understanding of many discharge plasmas in which multi-step processes are dominant. Under most circumstance the excitation rates for metastable atoms and/or molecules are much larger than rates for single-step ionization. The relatively long effective lifetimes of metastables leads to high densities of these species. Electron impact and other collisionsal processes can easily ionize or excite the metastables. In the 1950s Art also recognized that radiation trapping could dramatically extend the effective lifetime of atoms in resonance levels and effectively make those levels metastable [3]. He applied radiation trapping theory first to the measurement of excitation coefficients, but the implications were clear. Resonance levels can play a major role in multi-step ionization and excitation.

[1]A. V. Phelps & J. P. Molnar, Phys. Rev. **89**, 1202 (1953).
[2]A. V. Phelps, Phys. Rev. **99**, 1307 (1955).
[3]A. V. Phelps, Phys. Rev. **110**, 1362 (1958).

14:00

UF1 2 Personal Landmarks from the Legacy of Arthur Phelps JOHN LOWKE, *CSIRO Materials Science and Engineering* I have been influenced for my whole life by Art Phelps, more than by anyone else – other than my wife! I first heard of Art Phelps in 1960 when, in the middle of doing my PhD in Adelaide, South Australia, Frost and Phelps published their land-mark paper, not only on drift velocities, the subject of my PhD, but on Boltzmann analyses, which were to deliver detailed cross sections for all common gases. Later I dared to suggest to my university that one of my two external PhD examiners be Phelps, a move that led to me being accepted for a position at Westinghouse Research Laboratories in Pittsburgh for 6 years, with Phelps as my direct supervisor. Throughout this period, Phelps refused to be a co-author of any of my papers, leaving me with severe doubts as to what he thought of their quality! I list areas where insights from Phelps inspired the growth of new fruit. (1) That transverse and longitudinal electron diffusion coefficients differ, typically by a factor of two. (2) That averaging radiation absorption coefficients in electric arcs, using common weightings involving Black Body radiation, can and usually do lead to errors of orders of magnitude. (3) That CO_2 laser discharges are largely controlled by electron attachment rather than by diffusion or recombination. (4) That boundary conditions for electrons at metal electrodes in arc welding, are not zero, but from an astrophysical analogy, are zero when extrapolated to one mean free path beyond the surface. (5) That the metastable vibrational states of nitrogen become an energy gain rather than a loss process for low energy electrons as occur in electrical breakdown in air, resulting in increases of the ionisation coefficient by orders of magnitude. Coupled with the detachment of electrons from negative ions by singlet delta states of metastable oxygen molecules, sustaining discharge electric fields are reduced a factor of five. Phelps worked on this problem with me until a few months before he died.

14:30

UF1 3 Gas Breakdown, Low Current diffuse discharges, Townsend's theory: A Friday afternoon experiment ZORAN PETROVIC, *Institute of Physics University of Belgrade* Numerous aspects of the "standard model" of gas breakdown have been addressed in the past 20 years by Art Phelps and his coworkers. First, his studies of excitation coefficients were carried out in the Townsend regime where electric field is quasi uniform so swarm like conditions prevail. These studies have been extended to very high E/N where non-hydrodynamic effects were to be observed but were overshadowed in most cases by fast neutral excitation. Absolute calibration of emission provided a basis to obtain fast neutral cross section sets. This work necessarily overlapped with the left hand side of the Paschen curve and in extension of an ill fated data gathering experiment a review was made of all the processes that contribute to the secondary electron emission. It was shown that, if one includes all the processes, it is possible to fit the available breakdown data, Paschen curves and effective electron yields by binary collision data obtained in separate experiments. While performing measurements in the low current diffuse (Townsend) regime one can find negative differential resistance and oscillations. Both were explained by taking detailed information on properties of particles close to the cathode and small perturbations to the local field by the growing space charge. Last but not the least Phelps managed, with his coworkers to provide a phenomenology and predictions of the anomalously broadened profiles often observed in various discharges. In all those cases deep knowledge of atomic and molecular physics and of gas discharges were combined with best available data to produce quantitative (quantitative, quantitative) agreement with experiments. Coworkers: Dragana Maric. Supported by MPNTR project ON171037 and SANU project 155.

15:00
UF1 4 WORKSHOP BREAK

15:30

UF1 5 Expansion of Swarm Experiments at JILA to Microplasma Research KUNIHIDE TACHIBANA, *Osaka Electro-Communication University* Strongly attracted by the Art's remarkable work on metastable atoms in the 50s, I joined JILA as a posdoc at his laboratory in 1978. The assigned machine for me was a drift tube, and the first work was to check the validity of previous results. In a sense, I was tested of my skills as an experimentalist, but soon later I was able to start an original work on the measurement of excitation coefficient of rare gas atoms using the machine. We applied the laser absorption spectroscopy for the measurement of the excited atoms. The argon-ion-laser excited dye-laser at the lab for the light source was awfully unstable, but I was so lucky to have a wonderful support from John Hall, a Novel prize winner in 2005, to stabilize the laser system. After I came back to Japan in 1980, I extended the work to the measurement of Xe metastable (1s5) and resonant (1s4) atoms in a micro discharge cell of a plasma display panel. Then, I have deeply got into the world of microplasmas, exploring the new world with sophisticated arrays of microplasmas to find unusual properties as metamaterials for electromagnetic waves.

Throughout my whole research life, I would like to sincerely thank Art for the wonderful experiences with him at JILA.

16:00

UF1 6 Boltzmann analyses of swarm experiments over the years LEANNE PITCHFORD, *CNRS and Univ Toulouse* Art Phelps was one of the "grand old men" in field of gaseous electronics. He was a graduate student when the GEC got started and he attended almost all of the meetings over the years. During his remarkably long career, he produced a number of the classic papers in our field as a glance at Web of Science will show. Art was my mentor and friend, and I had the privilege of working with him for many years on various topics related mainly to electron scattering and transport in weakly ionized gases. In this talk, I will discuss the originality of some of his early work on these subjects in the context of their times, focusing in particular on his publications from the mid-1960's with his colleagues from Westinghouse Research Laboratories. These report the first numerical solutions of the Boltzmann equation for electrons, to my knowledge, and they inspired much subsequent work related to the extraction of quantitative information about low-energy electron scatting with simple gases from measurements of macroscopic parameters (mobility, diffusion,..). I will outline some of the work he and I did together in this topical area using more sophisticated numerical techniques. This and other work in the field eventually led to the establishment of the ongoing GEC Plasma Data Exchange Project which now involves a number of people (the LXCat team), as discussed in Tuesday's workshop. The LXCat team had completed work on noble gases and had just started working on evaluations of cross sections for simple molecules when Art died. We are fortunate to have had his involvement on these projects. Art had ideas for future work in these areas, and some are included in a long e-mail message from Art a couple of years ago that I will share because it includes some suggestions [to the community] for future work.

16:30

UF1 7 Electron Interactions with Excited Atoms and Molecules* STEPHEN BUCKMAN, *Centre for Antimatter-Matter Studies, Australian National University* Excited species, particularly those in long-lived metastable states, can have a profound effect on the behaviour of low temperature gas discharges. They often present a considerably different atomic or molecular structure to their ground state "parent" atom or molecule. In the case of rare gas atoms, several of their lowest lying excited states have structures resembling loosely bound, one-electron systems, similar to their nearest alkali neighbor in the periodic table. They have large dipole polarizabilities and, as a consequence, extremely large scattering cross sections for low energy electrons. Combined with their long lifetimes, large internal energy and reasonably high excitation probability, they become an important component of a discharge environment. This talk will review some of the work in studying these important excited states – their role in low temperature discharges was always a fascination for Art Phelps and he was a strong advocate for their detailed study.

SF1 **Plasmas for Nanotechnologies**
R. Mohan Sankaran
Room: Ballroom I

SF2 **Plasma Deposition**
Toshiaki Kato
Room: Ballroom II

SF3 **Biomedical Applications II**
Room: Nassau Room

SF5 **Electron Collisions with Atoms
and Molecules II**
Ali Belkacem
Room: Village Square

TF1 **Diagnostics II**
Thomas Schwarz-Selinger
Room: Ballroom I

TF2 **Low Pressure Plasma Modeling II**
Miles Turner, Vladimir Kolobov
Room: Ballroom II

TF3 **Thermal Plasmas, Negative Ion
Plasmas, and Dusty Plasmas**
Room: Nassau Room

TF5 **Electron-Molecule Collisions**
Thomas Rescigno, Steven Guberman
Room: Village Square

UF1 **Scientific Legacy of Arthur Phelps**
Room: Ballroom I

Epitome of the 66th Annual Gaseous Electronics Conference

08:00 MONDAY MORNING
30 SEPTEMBER 2013

AM1   **Workshop on Plasma Surface Interaction: From Fusion to Semiconductor Processing**
Room: Ballroom I

AM2   **Workshop on Weakly-ionized Non-equilibrium Air Plasma at Moderate and High Pressures: Generation and Maintenance, Modeling, Diagnostics and Applications**
Room: Ballroom II

18:00 MONDAY EVENING
30 SEPTEMBER 2013

BM1   **Welcome Reception**
Room: Ballroom Foyer

08:00 TUESDAY MORNING
01 OCTOBER 2013

CT1   **Poster Session I (8:00-9:30AM)**
Room: Ballroom Foyer

10:00 TUESDAY MORNING
01 OCTOBER 2013

DT1   **Basic Phenomena in Low Temperature Plasma Physics**
Adric Jones
Room: Ballroom I

DT2   **High Pressure Discharges: Dielectric Barrier Discharges, Coronas, Breakdown, Sparks I**
Room: Ballroom II

DT3   **Liquids I**
David Staack, Yakov Krasik
Room: Nassau Room

DT4   **Workshop on the Mysteries and Challenges of Negative Ion Sources**
Room: Fountain View

13:30 TUESDAY AFTERNOON
01 OCTOBER 2013

ET1   **Glows: DC, Pulsed, Microwave, Others**
Room: Ballroom I

ET2   **Microdischarges I**
Room: Ballroom II

ET3   **Green Plasma Technologies I**
Tomohiro Nozaki
Room: Nassau Room

ET5   **Workshop on the Plasma Data Exchange Project**
Room: Village Square

15:30 TUESDAY AFTERNOON
01 OCTOBER 2013

FT1   **Non-equilibrium Kinetics of Low-temperature Plasmas**
Room: Ballroom I

FT2   **High Pressure Discharges: Dielectric Barrier Discharges, Coronas, Breakdown, Sparks II**
Room: Ballroom II

FT3   **Liquids II**
Fumiyoshi Tochikubo
Room: Nassau Room

18:00 TUESDAY EVENING
01 OCTOBER 2013

GT1   **Tour of the Princeton Plasma Physics Laboratory**

08:00 WEDNESDAY MORNING
02 OCTOBER 2013

HW1   **Poster Session II (8:00-9:30AM)**
Room: Ballroom Foyer

10:00 WEDNESDAY MORNING
02 OCTOBER 2013

IW1   **PPPL Director Welcome and GEC Foundation Talk**
Stewart Prager, Rod Boswell
Room: Ballroom I & II

11:30 WEDNESDAY MORNING
02 OCTOBER 2013

JW1   **GEC Business Meeting**
Room: Ballroom I & II

13:30 WEDNESDAY AFTERNOON
02 OCTOBER 2013

KW1   **Inductively Coupled Plasmas**
Room: Ballroom I

KW2   **Microdischarges II**
Natalia Babaeva
Room: Ballroom II

KW3   **Green Plasma Technologies II**
Richard van de Sanden
Room: Nassau Room

KW5   **Electron and Positron Collisions with Atoms**
S.J. Ward, Dario Mitnik
Room: Village Square

15:30 WEDNESDAY AFTERNOON
02 OCTOBER 2013

LW1   **Plasma Etching**
Kaushik Kumar
Room: Ballroom I

LW2   **Plasma Modelling I**
Thomas Mussenbrock
Room: Ballroom II

LW3   **Biomedical Applications I**
Michael Keidar
Room: Nassau Room

LW5   **Heavy-Particle Collisions**
David Schultz, Michael S. Pindzola
Room: Village Square

08:00 THURSDAY MORNING
03 OCTOBER 2013

MR1   **Poster Session III (8:00-9:30AM)**
Room: Ballroom Foyer

10:00 THURSDAY MORNING
03 OCTOBER 2013

NR1   **Diagnostics I**
Jan Schäfer
Room: Ballroom I

NR2   **Plasma-surface Interactions**
Room: Ballroom II

NR3   **Plasma Boundaries: Sheaths, Boundary Layers, Others**
Mark Sobolewski, Dmytro Sydorenko
Room: Nassau Room

13:30 THURSDAY AFTERNOON
03 OCTOBER 2013

PR1   **High Pressure Discharges: Dielectric Barrier Discharges, Coronas, Breakdown, Sparks III**
Hirotaka Toyoda
Room: Ballroom I

PR2   **Capacitively Coupled Plasmas I**
Room: Ballroom II

PR3   **Gas Phase Plasma Chemistry**
Room: Nassau Room

PR5   **Electron Collisions with Atoms and Molecules I**
Oleg Zatsarinny, Hari Chaluvadi
Room: Village Square

15:30 THURSDAY AFTERNOON
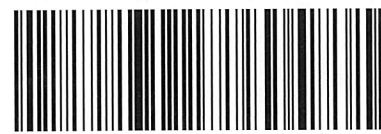**03 OCTOBER 2013**

QR1   **Microwave Discharges II**
Room: Ballroom I

QR2   **Capacitively Coupled Plasmas II**
Trevor Lafleur
Room: Ballroom II

QR3   **Magnetically Enhanced Plasmas**
Teresa de los Arcos
Room: Nassau Room

19:00 THURSDAY EVENING
03 OCTOBER 2 013

RR1   **Reception/Banquet**
Room: Ballroom