Plasma Science and Technology
Room: 210A - Session PS-ThA

Plasma Sources
Moderator: Cheng-Che Hsu, National Taiwan University

2:20pm **PS-ThA1 Control of Electron Heating and Ion Energy Distributions in Capacitive Plasmas by Voltage Waveform Tailoring based on a Novel Power Supply and Impedance Matching**, ***Birk Berger***, *J. Franek, St. Brandt,* West Virginia University*, M. Liese, M. Barthel,* Barthel HF-Technik GmbH, Germany*, E. Schuengel, M. Koepke, J. Schulze*, West Virginia University

We present a novel radio-frequency (RF) power supply and impedance matching to drive technological plasmas with customized voltage waveforms. It is based on a system of phase-locked RF generators that output single frequency voltage waveforms corresponding to multiple consecutive harmonics of a fundamental frequency. These signals are matched individually and combined to drive an RF plasma. Electrical filters are used to prevent parasitic interactions between the matching branches. By adjusting the harmonics' phases and voltage amplitudes individually any voltage waveform can be realized as a customized finite Fourier series. This RF supply system is easily adaptable to any technological plasma for industrial applications and allows the commercial utilization of process optimization based on voltage waveform tailoring for the first time. Here, this system is tested on a capacitive discharge based on three consecutive harmonics of 13.56 MHz in Argon with an admixture of Neon as tracer gas for Phase Resolved Optical Emission Spectroscopy (PROES). Measurements were performed for gap lengths of 30mm and 40mm, different pressures (p=3, 5, 200Pa) and varying applied voltages (V=120, 210V). According to the Electrical Asymmetry Effect, tuning the phases between the applied harmonics results in an electrical control of the DC self-bias and the mean ion energy at almost constant ion flux. A comparison with the reference case of an electrically asymmetric dual-frequency discharge reveals that using more than two consecutive harmonics significantly enlarges the control range of the mean ion energy. Additionally, the effect of tuning the phases on the electron heating and sheath dynamics within one low frequency cycle is investigated using PROES and correlated with changes of ion energy distributions at the electrodes.

2:40pm **PS-ThA2 Spectroscopic and Beam Current Characterisation of an RF Excited Argon Plasma Cathode Electron Beam Gun for Material Processing Applications**, ***Sofia del Pozo***, TWI Ltd. and Brunel University, United Kingdom of Great Britain and Northern Ireland*, C.N. Ribton,* TWI Ltd., United Kingdom of Great Britain and Northern Ireland, *D.R. Smith*, Brunel University

Details are given of a design of a novel RF excited plasma cathode gun that generates electron beams (EBs) for material processing applications including additive manufacturing, welding and cutting. Plasma EB sources offer solutions to the main problems with conventional electron beam guns, which use a thermionic cathode. Cathode wear from thermal cycling or ion bombardment is eliminated. EB power can be controlled by RF power modulation, which avoids the need for a grid electrode, and as a result reduces beam aberration. This technology has generated interest from various sectors of industry including additive manufacturing where rapid printing would be possible due to the high power provided by the electron beam, and at the same time fast beam pulsing can control material melting.

In this work, EBs were generated at accelerating potentials between 30 kV and 60 kV with beam powers of up to 1kW. The experimental setup allowed carrying out optical emission spectroscopy measurements simultaneously with beam current measurements.

A capacitively coupled plasma was generated in a cylindrical quartz chamber with 14 mm inner diameter. An RF power signal of 20 to 50 W at 84 MHz was applied between electrodes separated by 25 to 80 mm. Electrons were extracted from the plasma chamber to the vacuum chamber (at about 10^{-5} mbar) through an aperture (0.8 to 1.2 mm diameter) at the end of the plasma chamber by applying an accelerating voltage. Typically argon was used but EBs were also generated using krypton, helium and air. The pressure in the plasma chamber was controlled in the range 0.1 mbar to 1.5 mbar.

Optical emission spectroscopy measurements have been carried out in order to optimise plasma parameters for higher electron emission. This plasma diagnosis technique was selected as it is non-intrusive and allows estimation of important plasma parameters such as electron density and temperature. The spectra were correlated with electron emission. Ar – II lines were found to be much intense than Ar – I lines in those plasmas of higher electron emission. It was observed that the electron beam power was increased as the plasma chamber pressure decreased in one of the plasma chamber geometries. At any one plasma pressure, the beam power increased with RF power.

Further work is currently being carried out in order to increase the power of the electron beams generated. This includes revised plasma chamber designs and particle in cell simulation of the argon plasma.

3:00pm **PS-ThA3 Around the World of RF-Plasma Generation: A Brief Tour in 80 (half) Minutes**, ***Neil Benjamin***, Lam Research Corporation **INVITED**

This paper starts with a review of historical progress to reach the present day, when it is virtually universal to use RF excited plasmas to process semiconductor materials. This may extend to hundreds of process steps as Deposition, Etching, Stripping, Cleaning and Surface treatments are all in the RF-plasma repertoire. In order to do so, multiple factors and timelines have had to converge, including:

I. Electronics development, specifically RF technology and devices.

II. Plasma Technology A.K.A. Gaseous Electronics, specifically Dry Processing as applied to: Semiconductors, Flat panel displays, P-V solar panels, MEMs devices etc.

It is less than 70 years since the invention of active solid state electronics in 1947, but the semiconductor industry is now mature and consolidated while continuing to advance according to Moore's law. In the same period RF delivery systems have also progressed from high power vacuum tubes/valves to solid state devices in the 1980s. Most such RF systems use 50Ω transmission lines (for I.S.M.) so that matching networks are used to optimize power transfer to the antenna load impedance. Plasma technology use for semiconductor production did not start until the late 1960s / early 70s. In particular, despite the engineering complications of dealing with RF excitation, RF plasmas became popular because of their suitability for use with dielectric materials, and ameliorating the potential for damage caused by passing DC currents through delicate devices during manufacture.

In the second half of the paper we consider that while the technology involved in plasma processing has remained basically the same for nigh on 50 years, the demands on RF performance, control and consistency have escalated beyond all recognition. I will address some typical RF-plasma issues with examples taken from the current state of the art that continue to challenge us. These include igniting and delivering RF into the changing load impedance of a transient plasma, whether due to instability or by design. Another is dealing with the problem of stable and consistent excitation when there are multiple frequencies present either due to multiple source frequencies or due to the plasma generation of harmonics and mixing products. I will discuss how we achieve stable performance in terms of both uniformity and tool matching, in part by using sensor based control schemes. The question we must answer going forward is whether we can maintain or indeed improve this level of precision and performance, but do so ever more cost effectively.

4:00pm **PS-ThA6 Electron Beam Generated Plasmas Produced in Fluorine-Containing Gases: Characterization of Plasma-Surface Interactions**, ***Scott Walton***, *D.R. Boris,* US Naval Research Laboratory, *R.F. Fernsler,* Sotera Defense Solutions, Inc., *S.C. Hernández, Tz.B. Petrova, G.M. Petrov*, US Naval Research Laboratory

Electron beam generated plasmas are characterized by high plasma densities (> 10^{10} cm^{-3}) and very low electron temperatures (< 1 eV), making them well-suited for next-generation processing techniques, where high fluxes of low energy ions are desirable. In this work, we focus on characterizing the flux of species incident to substrates located adjacent to magnetically collimated electron beam generated plasmas produced in fluorine-containing gases (e.g. SF_6, C_xF_y, etc). In particular, the type and energy of the ions at the substrate surface are measured as function of relative gas concentration and substrate-to-beam distance. These results are complimented by bulk plasma measurements and modeling and then discussed in terms of the changes in surface directed ion flux caused by changes in electron temperature and density, and electronegativity associated with the introduction of attaching gases to very low T_e plasmas. This work is supported by the Naval Research Laboratory Base Program.

4:20pm **PS-ThA7 Electron Beam Generated Plasmas Produced in Fluorine-Containing Gases: Characterizing Plasma Parameters**, ***David Boris***, *G.M. Petrov,* Naval Research Laboratory*, R.F. Fernsler,* Sotera Defense Solutions*, Tz.B. Petrova, S.G. Walton*, Naval Research Laboratory

Electron beam generated plasmas are characterized by high plasma density ($>10^{10}$ cm^{-3}), and very low electron temperatures (<1 eV) making them well suited to next generation processing techniques where high fluxes of low energy ions are desired. In this work, we focus on the characteristics these plasmas in fluorine containing chemistries (SF_6, C_xF_y), due to their relevance to industrial etching applications. In particular we focus on the effect of dilute fluorine gas mixtures on the electron density, total plasma density, electronegativity, and electron temperature. These parameters are measured using a suite of probes, with plasma parameters calculated using an NRL developed Langmuir probe model which is particularly useful in complex multi-component plasmas. The results are then compared with a one-dimensional steady-state hydrodynamic model of electron beam generated Ar-SF_6 plasmas at low pressure in a constant magnetic field.

This work supported by the Naval Research Laboratory Base Program

4:40pm **PS-ThA8 Microwave Plasma Source Technologies: A Fifty Year Evolution from Unwanted Discharges to Free Radical Sources, to Low Pressure and Temperature Plasma Processing, to Gem Quality Diamond Synthesis**, ***Jes Asmussen***, Michigan State University **INVITED**

Opportunities to create, to experiment with and to apply microwave plasmas occurred after world war II when high power microwave sources became commercially available. The first applications of microwave plasmas used a small, micro plasma - like discharge as a harmonic generator, i.e. these plasmas were used to generate even higher frequency electromagnetic radiation. As the understanding of how to efficiently create and maintain a discharge improved, microwave plasma sources, as they were identified at that time, were applied to numerous high and low pressure applications such as down stream and in - plasma free radical sources for thin film deposition, etching and more generally to a large variety of plasma surface treatments. Under the influence of these applications, microwave applicator and plasma source technologies rapidly evolved and became more application specialized. Initially a plasma discharge scale up was identified as a challenge, but the ability to produce large, high density microwave discharges was demonstrated. Completely new subclasses of microwave discharges, such as electron cyclotron resonance (ECR) discharges, were identified. Eventually applications, such as microwave plasma - assisted synthesis of diamond, created important new microwave plasma technologies. Certainly over the past fifty years microwave plasma sources have evolved into an important and diverse group of technologies that have broad range of material processing applications.

In this presentation, the historical evolution of microwave plasma source technologies will be briefly reviewed. The current diverse group of the technologies now known as microwave plasma source technologies will be organized into subclasses. The physics and the methods of efficiently coupling microwave energy to both high and low pressure discharges will be identified and compared. The state - of - the - art applications such as single crystal diamond synthesis and ECR discharges will be reviewed. Finally the current microwave plasma source technologies will be compared with the more common, lower frequency excited capacitive and inductive plasma sources.

5:20pm **PS-ThA10 Insights to Scaling Remote Plasma Sources Sustained in NF_3 Mixtures**, ***Shuo Huang***, University of Michigan*, V. Volynets, S. Lee, I.-C. Song, S. Lu,* Samsung Electronics Co., Ltd., Republic of Korea*, J.R. Hamilton, J. Tennyson,* University College London, UK*, M.J. Kushner*, University of Michigan

Remote plasma sources (RPS) are used in microelectronics fabrication to produce fluxes of radicals for etching and surface passivation in the absence of damage to devices that may occur by charging and energetic ion bombardment. RPS reactors use distance, grids or other discriminating barriers to reduce or eliminate charged particle fluxes from reaching the surface of the material being treated. Nitrogen trifluoride (NF_3) is often used in RPS due to the efficiency with which F atoms are produced by dissociative attachment. RPS sustained in NF_3 gas mixtures, such as Ar/NF_3/O_2 increases the variety of reactive species produced, for example, N_xO_y. For certain applications it may be desirable to separately optimize, for example, F atom fluxes; and O atoms, or N_xO_y. This separate optimization could, in principle, be performed using pulsed power or pulsed gas sources. In this paper, we report on a computational investigation of RPS sustained in different NF_3 containing gas mixtures using pulsed power for low-damage plasma etching applications. Two modelling approaches were used – global modelling to investigate fundamental reaction mechanisms and 2-dimensional modelling to address the spatial dynamics of flow. A reaction mechanism was developed for plasmas sustained in mixtures containing Ar/NF_3/N_2/O_2. Cross sections for NF_x were generated using ab initio computational techniques based on the molecular R-matrix method. Results for RPS produced by both continuous wave power and pulsed power will be discussed, and comparisons made to experiments.

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