Plasma Science and Technology
Room 104B - Session PS-WeM

Plasma Sources and Novel Mechanisms for Generating Plasmas

Moderator: Sumit Agarwal, Colorado School of Mines

8:00am **PS-WeM1 Multifrequency Impedance Matching Solutions for Plasma Excitation by Tailored Voltage Waveforms*, Erik V. Johnson,*** Ecole Polytechnique, Palaiseau, France*; S. Dine,* SOLAYL SAS, France*; J.-P. Booth,* Ecole Polytechnique, Palaiseau, France

Tailored Voltage Waveforms (TVWs) and the Electrical Asymmetry Effect they induce in plasmas are useful tools to both optimize plasma processes and gain insight into the role of specific plasma parameters (ion bombardment energy, species flux) in processing outcomes. However, the multi-frequency nature of these waveforms, which are composed of a fundamental frequency in the MHz range and a number of its harmonics (e.g. 13.56MHz + 27.12MHz + 40.68MHz….), leads to a practical technical challenge, namely multi-harmonic impedance matching. Although impedance matching the 50 ohm output of an amplifier to a plasma processing chamber with a large reactive component is easily achieved for a single frequency using a passive component matchbox, doing the same at multiple harmonics is much more challenging due to the frequency response of every circuit element (including the chamber).

One strategy that has been employed and deployed as a commercial product is the use of multiple amplifiers, matchboxes, and filter sets, one for each frequency used. Although technically effective, using individual amplifiers for each frequency may not be the most cost-effective solution. Alternatively, we have previously proposed a technique to simultaneously match at multiple frequencies using a passive multi-frequency matchbox (MFMB), but this minimal-component solution is difficult to control due to variations in components affecting the response at pairs of frequencies.

In this work, we present results from a new design of MFMB using only passive components. Critically, this new design allows (1) independent control of the frequency response at each harmonic, and (2) the use of a single high-power amplifier. Circuit simulation results as well as experimental results are shown for a small area, laboratory plasma processing chamber during an argon plasma for three-frequency operation, and for fundamental frequencies between 9 and 15 MHz. It is demonstrated that although adjusting the matching condition for the fundamental frequency (1f) changes the matching for the other two (2f, 3f), the converse is not true; adjusting the matching on the higher harmonics does not impact that of the fundamental. Furthermore, we show that this improved matching is indeed due to better power transfer and not parasitic losses in the matching network.

8:20am **PS-WeM2 Effect of Tailored Voltage Waveforms on Surface Nanotexturing of Silicon in Capacitively Coupled SF_6/O_2 Discharges*, Guillaume Fischer,*** Institut Photovoltaïque d'Ile-de-France (IPVF), France*; E. Drahi, G. Poulain,* Total MS-Energies Nouvelles, France*; B. Bruneau, E.V. Johnson,* LPICM, Ecole Polytechnique, France

The nanotexturing of the surface of a crystalline silicon (c-Si) wafer for improved photovoltaic performance can be achieved through the use of an SF_6/O_2 reactive ion etching (RIE) capacitively coupled plasma (CCP). The resulting surfaces typically consist of nano-sized structures resembling cones (sizes ranging from 30 to 500nm) with little preferential crystallographic orientation. The process occurs through competing mechanisms involving Si etching by fluorine radicals, formation of in-situ micro-masking species, and physical etching by ions, all these mechanisms being strongly influenced by plasma conditions.

As has been done for previous processes and chemistries, we attempt to decouple the influence of various plasma properties through the use of Tailored Voltage Waveforms (TVWs), and thus obtain insights into the mechanisms involved in the dry nanotexturing of silicon. TVW excitation consists of adding harmonic frequencies with controlled amplitudes and phase-shifts to the RF (13.56 MHz) driving voltage, and allows one to quasi-independently control parameters such as species flux and ion bombardment energy (IBE). Furthermore, in an electronegative chemistry such as the SF_6/O_2 mixture, waveforms resembling "sawtooths" induce high ionization asymmetries due to plasma sheath dynamics, and may impact the type of reactive species arriving at the surface.

In this study, the phase-shift of the harmonic frequencies of the TVW excitation is varied at constant discharge power in an SF_6/O_2 mixture, therefore modifying (by an up to fourfold increase in absolute value) the self-bias voltage (V_{DC}) at the powered substrate holder and therefore the maximum IBE. The impact of varying the TVW shape is observed through both the plasma properties (V_{DC}, optical emission) and the morphological and optical properties of the obtained nanotexture. The effectiveness of the texture is quantified by the surface effective reflectance (R_{eff}) which is the average reflectance weighted by the solar spectrum irradiance.

It is here shown that the use of TVW excitation allows, at constant discharge power, to switch from a regime with no etching (almost no change of R_{eff}, no nanostructures observed) to a texturing regime where the decrease of R_{eff} scales with the IBE (R_{eff} decreasing up to 30% and nanocones observed). Moreover, new types of nanostructures have been observed for some particular etching regimes, showing partial dependence on the crystallographic orientation of the substrate.

8:40am **PS-WeM3 Plasma Enhanced CVD processes: Dual Frequency PECVD with pulsing of liquid precursors and PEALD for Selective Deposition*, Christophe Vallee,*** LTM, Univ. Grenoble Alpes, CEA-LETI, France*; R. Gassilloud,* CEA, LETI, MINATEC Campus*; R. vallat,* LTM, Univ. Grenoble Alpes, CEA-LETI*; F. Piallat,* Altatech, France*; M. Aoukar,* LTM, Univ. Grenoble Alpes, CEA-LETI*; P. Kowalczyk,* LTM - CEA/LETI, France*; P.D. Szkutnik,* LTM, Univ. Grenoble Alpes, CEA-LETI*; P. Noé,* CEA, LETI, MINATEC Campus*; A. Bsiesy, P. Gonon,* LTM, Univ. Grenoble Alpes, CEA-LETI **INVITED**

With this presentation we will address two topics concerning the development of specific Plasma Enhanced CVD processes for microelectronics applications: Dual Frequency (DF) with pulsed liquid injection of precursors and selective deposition.

First, we will talk about Dual Frequency processes for PECVD applications. Since the excitation frequency has extensive effects on the spatial distribution of species and their concentrations, the dissociation of the precursor can also be increased by crossing the discharge excitation frequency to the basic ion plasma frequency. This route is considered here with comparison and discussion over the improvements brought by Dual Frequency LF/RF plasmas in the case of thin metal gate (TiN) and Phase Change Material (GeSbTe) deposition. For this study we used 200 mm and 300 mm commercial PECVD tools from Altatech with a pulsed liquid injection of precursors. We will show that during TiN deposition the plasma enters a g-mode due to secondary electron heating. Then adding LF to RF modifies the sheath thickness of the plasma, increases the electron temperature of the gas and thus leads to strong modification of the carbon content, density and growth rate. For PCM applications, very different cycles (amorphous to crystalline) are obtained for GeTe materials elaborated in RF mode or DF mode. Moreover, we observe a very strong improvement of the gap filling capability of the process by using the DF mode.

The second part of this talk will be dedicated to the development of a selective deposition process by PEALD. One of the main challenges brought by the reduction of the transistor size below 10 nm is the development of selective deposition processes (for a self-forming Cu diffusion barrier for example). ALD is a suitable technique for selective deposition since it is a self-limited surface reaction process. The resulting selective process, called SeALD (Selective ALD) or AS-ALD (Area Selective ALD) is usually based on a specific surface treatment before deposition. Indeed, in ALD process, thin film nucleation depends strongly on the surface chemistry, so that by using a specific treatment one can transform a chemically reactive site into a nonreactive one. In this part, we propose a new selective ALD process, without surface treatment before deposition but using a Plasma assistance ALD process and by playing on the plasma chemistry. We will show for example that we are able to deposit selectively Ta_2O_5 oxide on top of metal (TiN) while no deposition is obtained on Si or SiO_2 surfaces. The process and its potential application will be described in more details during the talk.

9:20am **PS-WeM5 Customizing Ion Energy Distributions in Pulsed Plasmas with Chirped Bias Power*, Steven Lanham,*** *M.J. Kushner,* University of Michigan

Control of the ion energy distribution (IED) in plasma material processing reactors is necessary to maintain the critical dimensions (CD) needed to produce modern microelectronic devices. An effective way to customize IEDs is using pulsed power. For example, electronegative (e.g. halogen) plasmas used in etching processes form ion-ion plasmas during the power off period, where low energy ions can be preferentially extracted. This also allows for extraction of negative ions during the afterglow, which can help negate charge induced damage. Pulsed power parameters such as duty cycle and pulse repetition frequency need to be optimized for different electronegative plasmas chemistries due to varying attachment rates and heavy particle reaction mechanisms. The choice of frequency for the bias is a first-order decision in forming the IED, even in pulsed systems, which has in turn resulted in multi-frequency biases to aid in further customization. The use of multi-frequency biases brings additional complexity to pulsed systems.

In this work, based on a computational investigation, we discuss methods to produce customized IEDs in pulsed, electronegative inductively coupled plasmas. A 2-dimensional model, the Hybrid Plasma Equipment Model (HPEM), was used for this study. For pulsed biases in inductively coupled plasmas, IEDs will be discussed for various halogen plasma chemistries. Chirped biases in which the frequency is ramped during a pulsed period are discussed as a means to replicate IEDs that can otherwise only be formed in dual or triple frequency systems.

Work was supported by the Department of Energy Office of Fusion Energy Science and the National Science Foundation.

9:40am **PS-WeM6 Nonlinear Frequency Pull in Pulsed Capacitively Coupled Plasmas**, *J. Poulose, **Lawrence Overzet**, M.J. Goeckner,* The University of Texas at Dallas*; S. Shannon,* North Carolina State University*; D. Coumou,* MKS Instruments

Plasma ignition induces abrupt impedance changes due to the plasma sheath and bulk formation. These transitions can induce nonlinear changes in the instantaneous RF voltage and current frequencies despite the fact that the RF frequency is typically assumed to be fixed. These transitions are of particular interest in the application of frequency tuning of matching networks to maximize power transfer in pulsed plasma. In this presentation, we report on time resolved studies of the RF frequency and plasma impedance during pulsed plasma ignition using both electropositive (Ar) and electronegative ($CF_4/O_2/Ar$) gas mixtures. The center frequency is found to vary in time corresponding to fast changes in the complex plasma impedance when the plasma sheath is re-forming.

11:00am **PS-WeM10 Plasma Source Development for Fusion Relevant Material Testing**, ***John Caughman**, R.H. Goulding, T.M. Biewer, T.S. Bigelow, I.H. Campbell, S.J. Diem, A. Fadnek, D.T. Fehling, D.L. Green, C.H. Lau, E.H. Martin, P.V. Pesavento, J. Rapp,* Oak Ridge National Laboratory*; H.B. Ray, G.C. Shaw, M.A. Showers,* University of Tennessee*; P. Piotrowicz, D.N. Ruzic,* University of Illinois at Urbana-Champaign*; G.-N. Luo,* Chinese Academy of Sciences **INVITED**

Plasma facing materials in a magnetic fusion reactor have to tolerate plasma heat fluxes of 10 MW/m^2. The Prototype Materials Plasma Experiment (Proto-MPEX) is a linear high-intensity radio frequency (RF) plasma source that combines a high-density helicon plasma generator with electron and ion heating sections. It is being used to study the physics of heating over-dense plasmas in a linear configuration with the goal of producing up to 10 MW/m^2 of plasma heat flux on a target. The helicon plasma is operated at 13.56 MHz with RF power levels up to 100 kW. Microwaves at 28 GHz (~150 kW) are coupled to the electrons in the over-dense helicon plasma via Electron Bernstein Waves (EBW), and ion cyclotron heating (~30 kW) is via a magnetic beach approach. Plasma diagnostics include Thomson Scattering and a retarding field energy analyzer near the target, while a microwave interferometer and double-Langmuir probes are used to determine plasma parameters elsewhere in the system. Filterscopes are being used to measure D-alpha emission and He line ratios at multiple locations within the device, and IR cameras image the target plates to determine heat deposition both upstream and downstream of the helicon source region. High plasma densities have been produced in helium ($>3x10^{19}/m^3$) and deuterium ($>2x10^{19}/m^3$), with electron temperatures that can range from 2 to >10 eV. Operation with on-axis magnetic field strengths between 0.6 and 1.4 T is typical. The plasma heat flux delivered to a target can be > 10 MW/m2, depending on the operating conditions. Plasma parameters vary depending on the operating pressure/gas flow, and skimmer plates are used to try to control the neutral pressure in the device. The ion energy distribution varies radially/axially and is related to changes in the electron temperature and antenna coupling conditions. The helicon antenna coupling is being model with the COMSOL and VORPAL programs to help explain and guide operations. Details of the experimental results and operating parameters related to ion energies and delivered plasma heat flux will be presented.

11:40am **PS-WeM12 Linear Magnetron Magnet Pack for High Power Pulsed Magnetron Sputtering**, ***Jake McLain**, P. Raman, I.A. Shchelkanov,* University of Illinois at Urbana Champaign*; J. Hrebik,* Kurt J. Lesker Company*; B. Jurczyk, R. Stubbers,* Starfire Industries*; D.N. Ruzic,* University of Illinois at Urbana-Champaign

High Power Pulsed Magnetron Sputtering (HPPMS) is an ionized physical vapor deposition technique that utilizes high power pulses applied to the sputtering target. The high power densities allow for an increased percentage of sputtered particles to be ions, and the ions allow for more control over the deposition process. The enhanced control allows for improved film quality and surface adhesion when compared with DC magnetron sputtering (DCMS). The primary reason for the lack of industrial implementation is the intrinsically low deposition rate that HPPMS provides. The Center for Plasma-Material Interactions has designed a high deposition rate HPPMS magnet pack that produced comparable deposition rates in HPPMS when compared with a conventional magnet pack using DCMS for a 4-inch circular magnetron with a titanium target at 500W. This magnet pack also increased the HPPMS deposition rate twofold when compared with the conventional magnet pack using HPPMS [1]. To allow for industrial implementation of HPPMS, a similar high deposition rate magnet pack is designed and built for a linear magnetron, capable of being scaled to any desired length. This work focuses on the similarities and differences in the process and physics of the standard and new magnet packs. The properties explored in this work include deposition rate, deposition uniformity, plasma parameters, and film quality.

[1] P. Raman, et al., Surf. Coat. Technol. (2015), http://dx.doi.org/10.1016/j.surfcoat.2015.12.071

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