Plasma Science and Technology
Room: Galisteo - Session PS2-TuA

Plasma Sources
Moderator: D.J. Economou, University of Houston

2:00pm **PS2-TuA1 Plasma Study in Modulated Pulse Power (MPP) Magnetron Sputtering with Different Magnetron Configurations**, ***D.N. Ruzic***, *L. Meng, S. Jung, M.J. Neumann*, University of Illinois at Urbana-Champaign

As a derivative of high power pulsed magnetron sputtering (HPPMS), modulated pulse power (MPP) technology is used to apply arbitrary voltage waveforms to the cathode. It not only retains the distinctive features of HPPMS as the intense pulsed plasma density and potentially high ionization fraction of metal atoms, but also offers high degree of freedom for additional process control. In a 1000 cm^2 circular planar magnetron, discharges were initiated using a 10 kW average power MPP generator (capable of a pulse peak power up to 147 kW). To optimize the MPP discharge for the future applications, the effects of pulse waveforms and other discharge parameters on the plasma were studied first using a time-resolved triple Langmuir probe. A typical electron temperature (T_e) of 10 eV and an electron density (n_e) close to 10^{12} cm^{-3} during the pulses were determined. Higher pulse current, lower pulse repetition frequency, higher gas pressure and closer to the target were revealed to exhibit higher n_e, while T_e was also affected. The ion fluxes were then measured using an electrostatic gridded energy analyzer, showing typical ion energies of about 10 eV. Combined with a quartz crystal microbalance, the analyzer was further employed to measure the ionization fractions of sputtered metal atoms under various conditions. Finally, the effects of magnetron configurations were investigated using a specially-designed magnet pack in which both the positions and the strengths of the magnets were fully adjustable. Several configurations showed obvious superiorities to the normal balanced DC magnetron configuration, maintaining a higher pulse current and consequently a higher plasma density. A qualitative plasma model was proposed to explain the observed results and further understand the underlying mechanisms of the MPP discharge.

2:20pm **PS2-TuA2 Spatial Evolution of Plasma Generated VUV in a Microwave Surface-Wave Plasma**, ***J.P. Zhao***, *L. Chen, M. Funk, R. Bravenec, R. Sundararajan,* Tokyo Electron America Inc., *K. Koyama, T. Nozawa,* Tokyo Electron Limited, Japan, *S. Samukawa*, Tohoku University, Japan

Vacuum ultraviolet (VUV) radiations generated in low temperature plasmas (e.g., CCP and ICP) has been reported to cause wafer damage, alteration of morphology of polymers and electrical properties of dielectrics. Electron-hole pairs generated in dielectric films by VUV radiations can be trapped in dielectrics and interfaces. This results in charge buildup and dielectric breakdown as well as the decrease of device reliability. Synergistic effects of VUV exposure and energetic ion bombardment have been addressed to increase photoresist roughening. In order to improve the device and plasma process reliability, monitoring and evaluation of plasma generated VUV radiations have become important and highly demanded in plasma processing. Herein, characterization and spatial evolution of VUV radiations generated in a microwave surface-wave plasma is reported. Microwave surface-wave discharges operating within a wide power and pressure window can be used to produce large area plasmas of high density. Due to its inherent diffusion characteristics, apart from the discharge source, quiescent, uniform, and low-temperature Maxwellian plasma near wafer region can be obtained. In spite of these promising features, understanding the evolution of plasma generated VUV radiations can help the development of microwave surface-wave plasma based hardware and the design of process recipes. The plasma source used in this work consists of a radial line slot antenna (RLSA) which transmits 2.45 GHz microwaves into a large quartz resonator disk which then couples to the plasma. VUV radiations in RLSA plasma are monitored by measuring VUV induced electron-hole pair generation in dielectric films using VUV monitoring sensors developed by Samukawa et al.[1] Three kinds of VUV sensors consisting of SiO_2, Si_3N_4, and SiO_2/Si_3N_4 films are used, which monitor VUV radiations in the wavelength range of <140 nm, <250 nm, and >250 nm, respectively. Measurements in N_2, Ar, and O_2 plasma are carried out from 23 mm to 203 mm below top plate surface. A wide pressure-power spectrum has been investigated. Experimental results indicate that VUV radiations in RLSA plasma are dramatically reduced as a function of distance from the top plate. For better understanding on the evolution of VUV radiations in RLSA plasma, the electron energy distribution functions (EEDFs) are also measured using a Langmuir probe as a function of vertical location. Mechanisms on the evolution of VUV radiations are discussed based on the measured EEDFs and VUV absorption process.

[1] S. Samukawa et al., J. Vac. Sci. Technol. A 23(6), 1509 (2005)

2:40pm **PS2-TuA3 PM Helicons: A Better Mousetrap**, ***F.F. Chen****, UCLA **INVITED**

Helicon discharges are known to very efficient in generating high plasma densities at low pressures for such applications as etching. The reason for this efficiency is that helicon plasmas depend on resonant waves in a magnetic field which couple the rf energy into electrons in a complicated way involving nonlinear physics. To generate the magnetic field, commercial helicon reactors employ large, heavy electromagnets and a correspondingly large dc power supply to drive them. A new type of helicon discharge has been developed that uses the remote field of annular permanent magnets (PMs) and an array of small tubes that incorporate constructive interference of a reflected helicon wave [1-3]. With 3kW at 13.56 MHz, an 8-tube test device has produced argon plasmas of density 2-6 x 10^{11} cm^{-3} over ~20 x 50 cm areas with +/- 3-5% uniformity [4]. The source needs only 15 cm of vertical space. A code HELIC is used for the design of the wave properties, and a new code EQM has recently been developed to predict the equilibrium profiles of plasma and neutral densities and of electron temperature, With 27.12 MHz it is possible to design a very compact plasma thruster for spacecraft.

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1. F.F. Chen and H. Torreblanca, Plasma Phys. Control. Fusion **49**, A81 (2007).

2. F.F. Chen and H. Torreblanca, Phys. Plasmas **16**, 057102 (2009).

3. F.F. Chen and H. Torreblanca, Plasma Sources Sci. Technol. **16**, 593 (2007).

4. H. Torreblanca, Ph.D. thesis, UCLA (2008).

4:00pm **PS2-TuA7 Modeling of a Transformer-type Toroidal Plasma Source**, ***S. Rauf***, *Z. Chen, K. Collins*, Applied Materials Inc.

Many semiconductor processing applications including thin film deposition and chamber clean use reactive radicals, which can be efficiently generated using a remote plasma source. One popular remote plasma source design contains a toroidal plasma cavity with a few ferrite rings wrapped around the toroid. A radio-frequency (RF) magnetic field is induced in the ferrites using current loops around the ferrites, and this magnetic field generates a toroidal RF electric field within the plasma. The operation of this plasma source is not unlike a traditional transformer with a high permeability core. High density plasma can be generated over a large volume in these sources at moderate pressures (a few Torr), where traditional inductively coupled plasmas would have been localized in the vicinity of the inductive coils. Such a source design has also been used to generate high density plasmas for dielectric etching and plasma ion implantation. Despite the popularity of this plasma source design, it has not been modeled in detail to the best of our knowledge. This paper describes a 2-dimensional model for a magnetically-coupled transformer-type toroidal plasma source. The plasma model consists of the Poisson equation, the continuity equations for all species, and the electron energy equation. The drift-diffusion approximation has been used for the charged species. Induced electromagnetic fields and the resulting power deposition have been determined by solving the relevant Maxwell equations with an equivalent magnetic current source. The model also considers gas flow through the plasma source. The 2-dimensional model is applied to the simulation of Ar/NH_3 and Ar/O_2 plasmas in a toroidal plasma source driven at 400 kHz. A ring-shaped plasma is generated in the vacuum chamber by the electromagnetic fields. This plasma is fairly uniform, except near the gas inlet where the species composition is different due to rapid dissociation of the incoming reactive gases. Plasma characteristics are investigated over 0.5 – 3.0 Torr pressure and 500 – 3000 W power ranges. Electron densities in the $10^{17} - 5\times10^{18}$ m^{-3} range are observed for the conditions investigated and the incoming reactive gases almost completely dissociate in the plasma. Detailed plasma characteristics, structure of the electromagnetic fields, and composition of the resulting neutral species is discussed in the paper.

4:20pm **PS2-TuA8 Self-Consistent Electrodynamics of Large-Area High-Frequency Capacitive Plasma Discharge**, ***Z. Chen***, *S. Rauf, K. Collins*, Applied Materials Inc.

Large-area capacitively coupled plasmas (CCP) generated by high frequency (HF, 3-30 MHz) and very high frequency (VHF, 30-300 MHz)

***** 2009 Plasma Prize Winner

RF sources are used for thin film deposition in the production of thin film transistors for flat panel display and thin film photovoltaic solar panels. Economic considerations are driving a rapid increase in substrate size and adoption of VHF sources for improved film quality and higher deposition rate. As a consequence of these trends, electromagnetic wave effects are becoming the dominant factor in determining processing uniformity. Because the effective RF wavelength in plasma depends upon both RF frequency and plasma process conditions such as RF power and gas pressure, a self-consistent model including both RF power delivery system and plasma discharge is highly desired to capture a more complete physical picture of plasma behavior. In this paper, we present a three-dimensional model for self-consistently studying both electrodynamic and plasma dynamic behavior of large-area (> 8 m^2) CCP. The model couples Maxwell's equations with transport equations for charged and neutral species in the time domain. Maxwell's equations are discretized and solved using the finite-difference time-domain (FDTD) method. The plasma discharge is modeled by solving the continuity equations for charged and neutral species and the electron energy conservation equation. The complete RF plasma discharge chamber including RF power delivery sub-system, electrodes and plasma domain is modeled as an integrated system. The RF power source is naturally applied onto the transmission line of the RF feed system in the form of an electromagnetic wave. Based on the full-wave solution model, we are able to study the important limitations for processing uniformity imposed by electromagnetic wave effects in a rectangular reactor having electrode size of 3.05 m × 2.85 m. We examine the behavior of H_2 plasmas in such a reactor at a pressure of 2 Torr when we incrementally scale the frequencies from 13.56 to 200 MHz and the power from 20 kW to 80 kW. We show that various rectangular harmonics of electromagnetic fields can be excited as RF frequency or power is increased. These rectangular harmonics, mathematically described by the hyperbolic functions, can create not only the plasma profiles where plasma density is high at the center and low at the corners of the reactor, but also the profiles where plasma density is high at the corners and along the edges of the reactor and low in the inner area. Such highly nonuniform plasma distribution at VHF or high power level is challenging to compensate and has important implications for large-area plasma processing.

4:40pm **PS2-TuA9 Independent Control of Ion Energy and Flux in CCPs by the Electrical Asymmetry Effect**, ***U. Czarnetzki***, Ruhr-University Bochum, Germany **INVITED**

Technical plasmas are often generated by radio-frequency (RF) fields in the MHz regime. In particular, capacitively coupled RF plasmas have found wide industrial application ranging from semiconductor etching to thin film deposition as e.g. in large area production of solar-cells. In all cases the processes on the substrate surface are critically dependent on the energy and flux of the impinging ions. Therefore, independent control of these parameters is the major aim of various alternative concepts developed in the past. Despite some general progress, in practice independent control has been realized only within certain constrains.

The recently invented electrical asymmetry effect provides a novel solution by adjusting as a control parameter the relative phase between two harmonic RF frequencies [1]. This meets not only the above requirements in an almost ideal way but allows in addition for the first time breaking the symmetry in geometrically geometric discharges, which are common in large area processing. There the phase can be set so that the ion energy is increased on one electrode and reduced on the other or vice versa. The physics of the resulting non-linear system can be reduced to a few basic principles that allow an analytic treatment. The results of the analytical model are compared with particle-in-cell (PIC) / Monte Carlo (MC) simulations and experiments [1-6]. Although the system is characterized by a high degree of complexity all three approaches show remarkable agreements. Ultimately this leads to a detailed understanding not only of the dynamics of the electrical asymmetry effect but also of the physics of capacitively coupled plasmas in general.

Finally, first applications in industry on thin-film solar-cell production demonstrate superior performance by immediately more than doubling the deposition rate of silicon without loss in quantum efficiency.

References:

[1] Brian G. Heil, U. Czarnetzki, R. P. Brinkmann, T. Mussenbrock, Journal of Physics D: Applied Physics. 42, 165202 (2008)

[2] Z. Donkó, J. Schulze, B.G. Heil and U. Czarnetzki, Journal of Physics D: Applied Physics 42, 025205 (2009)

[3] Z. Donkó, J. Schulze, U. Czarnetzki, and D. Luggenhölscher, Applied Physics Letters 94, 131501 (2009)

[4] J. Schulze, E. Schüngel and U Czarnetzki, Journal of Physics D: Applied Physics 42, 092005 (2009)

[5] J. Schulze, E. Schüngel, U. Czarnetzki and Z. Donkó, Journal of Applied Physics 106, 063307 (2009)

[6] J. Schulze, E. Schüngel, Z. Donkó, and U. Czarnetzki, Journal of Physics D: Applied Physics, in print (2010)

5:20pm **PS2-TuA11 Inhomogeneous Magnetic Field Interaction with VHF and HF Capacitively Coupled Plasmas**, ***K. Bera***, *S. Rauf*, *K. Collins*, Applied Materials, Inc.

Both electromagnetic and electrostatic power deposition play important role in very high frequency (VHF) capacitively coupled plasma source to determine the plasma spatial profile. The electromagnetic effect enhances the plasma density near the chamber center, while electrostatic and inductive effects increase the density near the electrode edges. The electrostatic effect prevails for high frequency (HF) plasma sources. Secondary electron emission also plays an important role in determining the HF plasma profile. It has been shown earlier that the plasma profile generated due to VHF and HF sources can be modified using static magnetic fields. In this study, we further investigate the interaction of inhomogeneous static magnetic fields with plasmas. Various magnetic coil configurations, such as solenoid, cusp, mirror and dual solenoids, are considered. Our plasma model includes the full set of Maxwell equations in their potential formulation. The equations governing the vector potential, ***A***, are solved in the frequency domain after every cycle for multiple harmonics of the driving frequency. The electron transport coefficients become tensor quantities in the magnetized plasma. The coupled set of equations governing the scalar potential, Φ, and drift-diffusion equations for all charged species are solved implicitly in time. Static magnetic field from dc current sources has been simulated for different coil configurations, and imported to our plasma model. The plasma modeling result shows that radial magnetic field component limits electron loss to the electrodes and locally enhances the electron density. The axial magnetic field component primarily limits plasma diffusion in the radial direction thereby preserving the effect of improved electron confinement by the radial magnetic field component. For VHF plasmas, using solenoid coil, the magnetic field decreases the electron density in the chamber center and the peak in electron density gradually moves to the edge of the lower electrode. For HF plasmas, the peak density near the electrode edge increases with magnetic field. The effect of magnetic field on the plasma profile is enhanced using the cusp configuration. With dual solenoid, the radial and axial components of magnetic field are modified locally using different coil current ratios and directions. Depending on the nature and location of power deposition in the plasma chamber, the plasma profile is modified in different manner using various coil configurations, current directions, and current ratios.

5:40pm **PS2-TuA12 Properties of Corona Bar Discharges for Production of Preionizing UV Light**, ***Z. Xiong***, *M.J. Kushner*, University of Michigan, Ann Arbor

In electric discharge-pumped excimer lasers as used for photolithography sources in microelectronics fabrication, corona discharges are often used to provide UV photons to preionize the gas mixture. The preionization source, often called a *corona bar*, typically consists of a cylindrical metal rod surrounded by a dielectric. A discharge initiated by a high voltage pulse propagates around the surface of the corona bar, producing a surface-hugging avalanche wave similar to a gas phase streamer. The high electron temperature in the avalanche front produces radiating excited states that in turn produce the desired UV photons. We present results from a numerical study of an idealized corona bar discharge sustained in a multi-atmosphere $Ne/Ar/F_2/Xe$ gas mixture as used in ArF excimer lasers. The corona bar consists of a grounded metal cylinder surrounded by an annular dielectric layer of a few cm diameter. A point electrode (cathode) is located on the surface of the dielectric layer and is subject to a stepwise initial voltage change. The ensuing corona surface discharge was investigated using a 2-dimensional plasma hydrodynamics model with radiation photon transport. Continuity equations for charged and neutral species, and Poisson's equation are solved coincident with the electron energy equation with transport coefficients obtained from solutions of Boltzmann's equation. The ionization front, initiated from the point electrode, propagates along the cylinder surface (with speeds up to 3 x 10^8 cm/s that depend on the dielectric constant) charging the surface as it propagates. The ionization front usually stops before completing a full circle as the corona bar becomes progressively charged. The strength and propagation speed of the ionization wave are characterized by the electron density and temperature distributions along the cylinder circumference. The photon fluxes are collected on a surrounding circular surface. With radiation from short lived states such as Ne_2*, the UV emission sweeps around the corona bar coincident with the ionization wave. The effects of dielectric constants, gas mixture and voltage on the corona discharge dynamics will be presented.

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