Plasma Science and Technology
Room: 306 - Session PS2-WeM

Plasma Sources
Moderator: E.A. Hudson, Lam Research, C.A. Wolden, Colorado School of Mines

8:00am **PS2-WeM1 Generating Short Wavelength Light from Compact Sources - Challenges and Applications**, ***W. Holber***, *S. Horne, M. Partlow, J. Silterra, D. Smith, J. Ye, H. Zhu*, Energetiq Technology, Inc. **INVITED**

Across a range of scientific and technological applications, there is a need for more capable short-wavelength light sources. In semiconductor manufacturing, critical dimensions are now in the nanometer range and EUV at 13.5 nm is under active investigation as a lithography source. In biotechnology, structural information on proteins requires UV down to 170 nm and internal cellular features are imaged using 2.3-4.3 nm radiation. Lasers can produce significant amounts of light at specific wavelengths in the UV, but do not provide broad wavelength coverage either in the UV or soft x-ray spectral regions. Synchrotrons are a source of bright, incoherent radiation at wavelengths from hard x-ray through DUV, but are based in large, centralized facilities. Incoherent light sources that are lab-based provide an alternative to synchrotrons in a growing number of applications. We will present results from a compact z-pinch plasma source customizable to different wavelengths in the EUV and SXR[1] range, generating up to 10 Watts of power at 13.5 nm, and a laser-driven lamp source of light from 170 to 800 nm. Both provide uniquely bright output over a range of applications.

[1] Work on SXR sources funded in part by NIH Grants 5R44RR022488-03 and 5R44RR023753-03.

8:40am **PS2-WeM3 3-Dimensional Model for Magnetized Capacitively Coupled Plasma Discharges**, ***S. Rauf***, *J.A. Kenney, K. Collins*, Applied Materials, Inc.

Static magnetic fields are often used in plasma processing systems to improve plasma confinement, modify plasma spatial profile or adjust other plasma characteristics. Aside from some simple magnetic field configurations, magnetized plasmas have a complex spatial structure and significant physics is missed in reduced (0, 1 or 2) dimensional models. A 3-dimensional fluid plasma model is used to understand the operation of magnetized capacitively coupled plasmas operating at 13.56 and 180 MHz in this paper. Both electropositive (Ar) and electronegative (O_2) gases are considered. To simplify interpretation of results, simulations have been done for an axi-symmetric reactor geometry. Static magnetic field is generated using current carrying wires, where several wire configurations that generate converging, diverging and uniform magnetic fields in the plasma region are considered. Our 3-dimensional 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 each cycle for multiple harmonics of the driving frequency. The coupled set of equations governing the scalar potential, φ, and drift-diffusion equations for all charged species are solved implicitly in time. The model also includes the electron energy equation, Kirchhoff equations for the external circuit, and continuity equations for neutral species. The effect of static magnetic field is included through the charged species transport properties, which become tensor quantities in the presence of a static magnetic field. Without magnetic field, electron density peaks in the center of the chamber when the plasma is generated using a 180 MHz source. The 180 MHz plasma is also symmetric because of considerable distance from the chamber walls. When a static magnetic field parallel to the electrodes is applied, ExB drift in the sheath regions shifts the peak in plasma density off-axis. As the 180 MHz plasma is symmetric, ExB drift occurs in opposite direction in the two sheaths, which leads to an overall shearing of the plasma. Electron density peaks near the electrode edges in the 13.56 MHz plasma and the plasma is highly asymmetric. Application of magnetic field and the resultant ExB drift lead to overall shifting of the low frequency plasma in the ExB direction.

9:00am **PS2-WeM4 Effects of Very High Frequency Source Mixing and Inter-electrode Gap on Plasma Characteristics**, ***K. Bera***, *S. Rauf, K. Ramaswamy, K. Collins*, Applied Materials, Inc.

Capacitively coupled plasma (CCP) discharges are widely used for dielectric etching in the semiconductor industry. Very high frequency (VHF) power sources are being employed to generate plasmas for dielectric etching due to VHF's various benefits including low plasma potential, high electron density, and controllable dissociation. Electromagnetic effects tend to make the spatial and temporal behavior of VHF plasmas complex with a rich set of new physics. If plasmas are generated using multiple VHF sources, one can expect interaction between the sources and plasma characteristics to be different from those due to individual frequencies. We investigate the effects of VHF frequency mixing on plasma characteristics in this presentation. The study is done for a range of inter-electrode gaps. Both computational modeling and experiments are utilized. Our plasma model includes the full set of Maxwell equations in their potential formulation. The equations governing the vector potential are solved in the frequency domain after every cycle for multiple harmonics of the driving frequency. Current sources for the vector potential equations are computed using the plasma characteristics from the previous cycle. The coupled set of equations governing the scalar potential and drift-diffusion equations for all charged species are solved implicitly in time. Plasma simulation results show that electron density is usually higher in the center of the chamber at high frequencies due to a standing electromagnetic wave. Electrostatic effects at the electrode edges tend to get stronger at low VHF frequencies. Electron energy distribution function (EEDF) appears to be two-temperature Maxwellian. Ion saturation current measurements using a Langmuir probe show that ion saturation current, and hence plasma density, peaks in the chamber center at high VHF frequencies. As power at low VHF frequencies is added, ion saturation current increases at the edge of the electrodes and electrostatic effects become stronger. Even at high VHF frequencies, inductive heating at the electrode edges becomes strong for small inter-electrode gaps. This tends to increase electron density at electrode edge relative to the chamber center. As the gap is increased, the plasma is able to diffuse to the chamber center. The electromagnetic effects that dominate near the chamber center become more important than electrostatic effects.

9:20am **PS2-WeM5 The Impact of Electrode Gap and Gas Injection on Plasma Etch Uniformity**, *G.M. Amico*, ***M. Block***, *S. Sirard, J. Guha, A. Leming, A. Marakhtanov, E.A. Hudson, M. Srinivasan*, Lam Research

At the 32nm node and below, etch rate and CD uniformity requirements for multi-layer low k dual damascene integration schemes continue to tighten. Additionally, more focus is being placed on the process uniformity at the outer 5mm of the wafer. This paper examines the effect of electrode gap and the distribution of gas injection in a capacitively coupled reactor with confined plasma and adjustable gap. Radial etch rate and CD uniformity were studied for different films, with emphasis on multi-layer DD integration schemes. Mechanisms for the influence of electrode gap on process uniformity are different for ion limited and neutral limited etch regimes. Oxide etch rate radial uniformity as a function of gap shows a correlation to ion flux measurements. Narrower gaps tend to increase edge etch rates for all films, but the gap for optimal uniformity is dependent upon film composition. For multi-layer processing, the overall uniformity can be improved by employing different gap settings for each process step.

9:40am **PS2-WeM6 2 m Long-Line Plasma Production by Evanescent Microwave in a Narrowed Rectangular Waveguide**, *H. Shindo*, ***Y. Kimura***, Tokai University, Japan

Long line-shaped plasmas are inevitable in material processing in manufacturing industries, such as flat panel displays (FPDs) and surface modification of large- area thin films. In this work, we studied a newly proposed method of large-scaled line plasma generation. In this method, microwave power of frequency of 2.45 GHz in a narrowed and flattened rectangular waveguide is employed to produce plasma. Since the width of waveguide is very close to the cutoff condition, the wavelength of microwave inside the guide is very much lengthened, providing a condition of long uniform line plasma generation. The narrowed rectangular waveguides of 1.5 and 2.0 m in length and 5mm in height were examined. The width of the waveguide could be varied from 59 to 61 mm. The waveguide has a long slot of 5 mm width on the top surface to launch the microwave into the discharge plasma chamber. The plasmas of Ar nad He at the pressures of 0.1 to 5Torr were generated by employing an extremely long microwave wavelength. It was observed that the microwave electric field became more uniform as the wave guide width was narrowed, indicating that the plasma production is due to the mechanism expected. The optical emission line measurements in Ar and He plasmas also confirmed that the uniform plasma was produced in the entire region of 1.5 m and 2.0 m. The probe measuremnts of the plasma were also made, indicating that the plasma uniformity was within 10 % in the entire plasma. Thus we conclude that the present method of plasma production is quite advantageous for large area processing. Plasma extraction was also successfully tested.

10:40am **PS2-WeM9 Development and Characterization of a Radical Beam Source Based on Surface Waves for Plasma-Surface Reaction Studies**, ***R. Khare***, University of Houston, *L. Stafford*, Université de Montréal, Canada, *J. Guha, V.M. Donnelly*, University of Houston

Previously, we studied recombination of Cl and O on plasma-conditioned anodized aluminum and stainless steel surfaces. Cl and O atoms formed in chlorine or oxygen plasmas impinged on a cylindrical substrate that was rapidly rotated such that points on the surface were exposed to the plasma and then to a differentially-pumped analysis chamber equipped with either an Auger electron spectrometer or a mass spectrometer. Langmuir Hinshelwood (LH) recombination was observed by monitoring desorption of Cl_2 and O_2 with the mass spectrometer or through a pressure rise. In these previous experiments, however, Eley Rideal (ER) recombination (if it occurs) could not be detected because it would take place instantaneously in the presence of atom flux, and hence would cease as soon as the sample left the plasma. To observe the ER component, as well as to isolate LH recombination in plasmas with multiple radical species (i.e. most plasmas), a separate radical beam source is needed in combination with the plasma and spinning substrate. With this in mind, we investigated a surface-wave chlorine plasma operating at 2.45 GHz and sustained in a 8 mm O.D. quartz tube using a gap-type surfatron wave launcher. With added traces of rare gases, optical emission spectroscopy was used to measure Cl and Cl_2 densities and the electron temperature, T_e, at 50 mTorr as a function of distance from the wave launcher. The Cl(792.4 nm)-to-Xe(828 nm) emission intensity ratio, reflecting the Cl number density, decreased with distance from the launcher, while the Cl_2 (306 nm)-to-Xe emission ratio that is proportional to Cl_2 number density, peaked near the launcher. The Cl_2 percent dissociation obtained from the calibrated Cl_2 -to-Xe emission ratio was very high (97 %) near the launcher, and remained high (89 %) until the end of the plasma column (about 12 cm from the launcher for an absorbed power of 90 W). By selecting Ne, Ar, Kr, and Xe lines excited from the ground state which are characteristic of the high energy portion of the electron energy distribution function (particularly Ne), we found that T_e increased from 5 to 10 eV as the observation point was moved away from the launcher. On the other hand, a nearly constant value of $T_e = 3.1 \pm 0.6$ eV was obtained using Ar, Kr and Xe lines excited to a significant extent through impact with lower energy electrons. Mechanisms for such high energy tails will be discussed.

11:00am **PS2-WeM10 Production-Worthy Pulsed ICP Plasma Processes**, ***S. Banna***, *V. Todorow, K. Ramaswamy, A. Agarwal, S. Rauf, K. Collins*, Applied Materials, Inc.

The transition to 45nm and smaller technologies has triggered intensive research effort among academic and industrial communities in search of wider range of plasma operating conditions aiming to improve etch processes for finer features. Pulsed radio frequency (PRF) plasmas are promising to achieve such a goal. It has been demonstrated through numerical modeling and basic experimental studies that PRF plasma might exhibit higher selectivity, improved uniformity, and minimal charge damage in many etch processes. However, due to the lack of efficient RF power delivery, PRF has only been utilized in a limited number of large-scale commercial applications. Particularly, two main PRF regimes were utilized in inductively coupled plasma (ICP) reactors. In the first, the source operates in the continuous wave (CW) RF mode while the bias operates in the PRF mode. In the second, the source power is pulsed while having the bias operating in the CW mode. The main challenge has been to minimize the amount of reflected power. Specifically, high bias reflected power was observed for low-pressure processes with source pulsing, in which time-modulation of the source power is highly coupled to the bias. The high reflected power is mainly due to the mechanical nature of conventional dynamic matching networks used to reduce the reflected power. The response time of the mechanical adjustment is of the order of hundreds of milliseconds. Hence, the match cannot track the changes in the time-modulated power as the pulse frequencies of interest are greater than 1kHz. There is a vital need for new capability to reduce the reflected power in sub-millisecond time scale. Recently, we have developed production-worthy, reliable and robust PRF plasma operation in a commercial ICP reactor that provides an expanded window of operation by establishing multiple techniques for optimizing RF power delivery in PRF mode. By so doing the matching response time is reduced to as low as a few microseconds. Accordingly, larger number of etch processes operating at pulsed plasma mode are feasible. The robustness of the system is manifested by its ability to provide a variety of RF modes of operation, furnishing more flexibility in etch processes design. By utilizing these modes in ICP reactor, it was demonstrated that one can improve uniformity, enhance selectivity and eliminate micro-trenching in real production etch processes. Supporting plasma modeling and diagnostics will be discussed.

11:20am **PS2-WeM11 Two Cannel Filtered Vacuum-arc Plasma Source for Composite Coatings Deposition**, *I.I. Aksenov, D.S. Aksyonov, V.V. Vasilyev, A.A. Luchaninov, E.N. Reshetnyak*, ***V.E. Strel´nitskij***, NSC "Kharkov Institute of Physics and Technology", Ukraine

The new two-cathode filtered vacuum arc plasma source is considered. The source contains two plasma generators with magnetic stabilization of an arc and focusing of a plasma stream. For removal of macroparticles from plasma generated the two-channel magnetic filter with T-shaped plasma duct is used. When both generators are simultaneously in operation the plasma streams emitted by them go through the entrance sections of the plasma duct into its exit section, and are transported up to a substrate. By means of a flat matrix probe the measurements of an ion current and its density distribution at the output plasma stream cross-section have been carried out. The ion current at the filter exit strongly depends on intensity and geometry of magnetic fields in the plasma guiding channels and on pressure of argon gas in the system. At arc current of 100 A of each generator the output ion current was 5.5 A. At creation of an acute-angled magnetic fields distribution with the annular cusp near the filter exit, the conditions providing leveling of the ion current density distribution at the probe surface and thickness of the condensed film distribution along the substrate surface were attained. When both generators with the cathodes of different materials (Al and Ti) were simultaneously in operation, coatings with rather homogeneous composition were grown at the motionless flat substrate of 60 mm in diameter. Aluminum percentage dispersion was about 70 %. At operation of only one generator the output plasma stream density distribution was strongly asymmetrical. The leveling and balancing of the distribution in this case also was reached by creation of the acute angle magnetic film at the system exit. At use of composite cathodes (Ti, Si) the structure of condensate deposited was non-uniform. Leveling of the components concentration distribution on a spot of condensation was reached choosing the argon pressure in the system and the substrate negative bias voltage. The gained results of researches are rather perspective for growth of high-quality composite coatings including nanostructural.

Authors Index

Bold page numbers indicate the presenter