Plasma Science and Technology

Room: 607 - Session PS2-TuA

Plasma Sources

Moderator: D.L. Keil, Lam Research Corporation

1:40pm **PS2-TuA1 Influence of Gas Heating on Microplasma I-V Characteristics**, ***S.G. Belostotskiy***, *V.M. Donnelly, D.J. Economou*, University of Houston

Experimental I-V characteristics of DC microdischarges in helium were obtained at different operating pressures (P = 300 - 800 Torr). Since the interelectrode gap was relatively small (L = 300 µm), the voltage drop across the discharge was approximately equal to that across the cathode sheath. It was found that the scaling laws obtained by the classical theory of the cathode layer developed by von Engel and Steenbeck (i.e., the cathode voltage is a function of current density divided by the square of the pressure - $V_c = f(j/p^2)$) are not applicable to microdisharges due to the influence of gas heating. For example, the voltage drop at p = 700 Torr was 40 Volts higher than that at p = 300 Torr for the same reduced current density J = 3 $\mu A/(cm^2*Torr^2)$. A new semi-analytical model of the cathode layer that accounts for neutral gas heating was developed. Model predictions were in agreement with the experimental I-V characteristics. The model can be used to quantify the influence of neutral gas heating on microdischarge performance.

2:00pm **PS2-TuA2 RF Discharge under the Influence of a Magnetic Field**, ***E.V. Barnat***, *P.A. Miller,* Sandia National Laboratories, *A.M. Paterson*, Applied Materials

We examined the effects of an externally applied magnetic field (0 to 150 Gauss) on a capacitive 13.56 MHz argon discharge in a Gaseous Electronics Conference (GEC) reference cell. The electrical characteristics of the discharge were measured as functions of applied magnetic field and rf power. At fixed power the rf voltage decreased with increasing magnetic field. The discharge impedance was predominantly capacitive and became more resistive as the electron mobility decreased with increasing magnetic field. We also measured the effect that the magnetic field had on the spatial distribution of the plasma in vertical planes parallel and perpendicular to the direction of the magnetic field using Langmuir probes, optical emission, and laser induced fluorescence. Due to ExB forces, the distribution of excited states in the plasma remained radially symmetric in the plane parallel to the magnetic field and became skewed in the plane perpendicular to the magnetic field. The degree of skew depended on the state probed. Finally, we examined the temporal evolution of the electric fields in the plasma. In the presence of magnetic field, the sheath thickness decreased and most of the voltage drop was contained within the sheath. Consistent with dc voltage trends, there was no significant sheath reversal observed at higher magnetic fields. Comparisons of the results presented here are made to trends predicted by models and simulations found in the literature.

2:20pm **PS2-TuA3 Characterization of a High Power Surface Wave O_2/N_2 Plasma Jet for Removing Photoresist from Semiconductor Wafers**, ***M. Bhargava***, *B. Craver, H. Guo,* University of Houston, *A.K. Srivastava,* Axcelis Technologies, *J.C. Wolfe*, University of Houston

We describe a plasma system for removing photoresist from silicon wafers where reactant gas flowing in a quartz tube is activated by a high power, 2.45 GHz surface wave discharge at pressures near 80 Torr.The plasma applicator is based on Moisan's 'surfaguide' design[1] where the discharge tube passes through a thin-walled coupling aperture in a reduced-height wave-guide section. Microwave electric fields loop out of the aperture and launch surface waves in both directions along the interface between the discharge tube and the plasma. The directional flow (3slm) of process gas in the tube (6 mm inside diameter) effectively suppresses the discharge on the upstream side of the waveguide. This same flow, in conjunction with the downstream surface wave, produces a plasma jet that emerges from the end of the discharge tube and carries hot, activated gases to a scanning wafer below.The discharge tube is cooled by a counter-flow of clean, dry air confined in a coaxial outer tube; this enables extended operation at 2.5 kW for O_2/N_2 discharges. The wafer is clamped to a heated, 200 mm chuck with a backside pressure of about 35 Torr. An x-y stage, actuated by in-vacuum linear motors, translates the wafer with speed and acceleration up to 1.1 m/s and 2 g, respectively. The efficiency of converting microwave power to thermal jet power is 21% and 19% for respective substrate-to-source distances of 0.9 cm and 2.9 cm, independent of oxygen concentration. For an $O_2:N_2$= 9:1 plasma jet operating at 2.5 kW, 80 Torr pressure, and a flow of 3slm, the etched track profile is Gaussian in shape with a full-width-at-half-maximum of 1.5 cm. A serpentine raster pattern with 7 mm pitch is used to cover an entire 200 mm wafer. The time to clear 1.2 µm thick, unimplanted photoresist is about 10 seconds for a 70 cm/s scan speed and 200 °C chuck temperature. This corresponds to an instantaneous etch rate of about 4000 µm/min. A detailed analysis of the transient heating process will be presented at the conference. Acknowledgements: Partially supported by the Texas Center for Superconductivity at the University of Houston. The authors are grateful to Ivan Berry for insightful discussions. The opinions expressed are solely the responsibility of the authors.

[1] M. Moisan et al., IEEE Trans. Plasma Sci. PS-12, 203-214 (1984).

2:40pm **PS2-TuA4 Effect of DC Superposition on the Selective Etching of SiO_2 over Si_3N_4 in Dual Frequency Capacitively Coupled Plasma**, ***S.-O. Lee***, *M.-S. Lee, S.-H. Cho, Y.-S. Cho, S.-C. Moon, J.-W. Kim*, HYNIX Semiconductor Inc., Republic of Korea

The characteristics of negative external DC superposition with the top electrode in dual frequency C_4F_6/O_2/Ar gas capacitively coupled plasma (CCP) on the selective etching of SiO_2 over Si_3N_4 have been studied as a function of supplying DC voltage, ranging from 0V to -1500V. It is reported that the accelerated 2nd electron which is generated near top electrode sheath by using DC superposition irradiates the wafer, and polymer molecular structure such as C/F ratio and C-C bond structure etc. is reformed. To analyze the effect of DC superposition in dual frequency CCP source, we investigated the chemical species such as CF_2 radicals and other radicals that have influence on polymerization, in the gas phase with optical emission spectroscopy (OES). The thickness and components of fluorocarbon polymer on etched surface were investigated with high resolution transmission electron microscopy (HR-TEM) and X-ray photoelectron spectroscopy (XPS).

3:00pm **PS2-TuA5 Frequency and Pressure Effects in Plasma Etching of High Aspect Ratio Features in Dielectric Films**, ***E.A. Hudson***, *C. Hayden, D.L. Keil, S. Engelmann, C. Rusu, L. Romm, M. Srinivasan*, Lam Research Corp.

Microelectronics processing requires etching of many different dielectric films and structures. Among these applications, some of the most challenging are the etching of high aspect ratio contacts and memory cells. Dual-frequency capacitively-coupled discharges at high power are widely used for these applications. Typically a lower excitation frequency provides the capability for high energy ion bombardment while a higher frequency allows decoupled control of plasma density. This paper examines the effect of applying three different excitation frequencies at the wafer electrode to access this process regime, using a mechanically confined plasma in a narrow-gap etch reactor. The effects of process pressure and 27MHz vs 60MHz, in combination with 2MHz, were characterized by plasma diagnostic measurements of ion flux and radical densities. Dense arrays of high aspect ratio holes were etched to measure the feature-level influence of these process control parameters. Results indicate that the combination of 60MHz and lower pressure allows operation at higher ion:radical flux ratios, which may help to prevent early etch stop. Additionally the radical chemistry is controlled by the ratio of 27MHz to 60MHZ power. Therefore the combined use of three frequencies improves the tuning of feature profiles and the control of striations.

4:00pm **PS2-TuA8 Numerical Investigation of Wave Effects in High-Frequency Capacitively Coupled Plasmas***, ***Y. Yang***, *M.J. Kushner*, Iowa State University

The trend in dielectric etching using capacitively coupled plasmas is use of multiple frequencies where a high frequency (tens to hundreds of MHz) dominates ionization and a low frequency (a few to 10s MHz) is used to control ion energy distributions. As the effective wavelength in the plasma waveguide represented by the reactor decreases with increasing frequency, electromagnetic wave propagation effects become a concern and may give rise to limitations on processing uniformity. These effects have been investigated experimentally but are difficult to address computationally in arbitrary geometries due to the coupling between the electromagnetic and the electrostatic fields, the latter of which is responsible for the formation of the sheath. In this talk, we discuss results from a computational investigation of high frequency effects in capacitively coupled plasmas. A full Maxwell solver based on the concept of vector and scalar potentials, and capable of resolving wave effects in a self-consistent manner in arbitrary geometries, was developed and incorporated into the Hybrid Plasma Equipment Model, a two-dimensional hybrid simulation. In particular, the capability to address multiple frequencies in the time domain are included. To properly capture high frequency heating, excitation rates are provided by spatially dependent electron energy distributions generated by a Monte Carlo simulation. The method of solution will be discussed and comparisons made to using a conventional electrostatic method for electric fields. Results from investigations of dual frequency CCPs (low frequency < 10 MHz, high frequency > 50 MHz) in 10s of mTorr polymerizing and non-polymerizing gas mixtures will be discussed. Assessments of the change in power deposition profile as a function of frequency will be made.

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4:20pm **PS2-TuA9 Physics of Very High Frequency (VHF) Capacitively Coupled Plasma Discharges**, ***S. Rauf***, *K. Bera*, *K. Collins*, Applied Materials, Inc.

Capacitively coupled plasma (CCP) discharges are widely used for dielectric etching in the semiconductor industry. Operating frequencies, especially the source frequency in multi-frequency CCP systems, have generally increased in recent years to be able to generate high electron-density discharges with moderate ion energy. Concomitantly, economic considerations are driving towards radially larger plasma discharges. The combination of higher driving frequencies and larger plasma size means that electromagnetic effects start to play a more important role in determining plasma behavior. Understanding the physics of VHF plasmas is therefore critical for assessing the scalability of CCPs to future generations of dielectric etching technologies. This paper uses a computational model to elucidate the physics of VHF CCP discharges. The 2-dimensional 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. 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, φ, and drift-diffusion equations for all charged species are solved implicitly in time. The model also includes the electron temperature equation, Kirchhoff equations for the external circuit, and continuity equations for neutral species. Our simulations focus on a 180 MHz CCP discharge, and examine the effect of inter-electrode spacing, driven electrode diameter, grounded electrode size and magnetic field on the plasma characteristics. It is found that the electrostatic component of the electric field peaks in the sheath region, where there is an imbalance between positive ion and electron concentrations. Electromagnetic fields are generated by current flowing through the discharge. The electromagnetic component of the electric field peaks in the center of the chamber due to the standing wave effect. The electromagnetic fields have a strong influence on charged species location and concentration at 180 MHz. However, besides the operating frequency, the plasma reactor design (inter-electrode spacing and electrode sizes) also determines the relative importance of the electromagnetic fields in plasma dynamics.

4:40pm **PS2-TuA10 Electron Heating Mechanisms, Mode Transitions, and Non-Uniformities in Dual Frequency Capacitive Discharges**, ***P. Chabert***, École Polytechnique, France **INVITED**

The physics of capacitive discharges has recently been reinvigorated with the rise of interest in multiple-frequency excitation and the related need to widen the range of frequencies that are used. A major attraction of dual-frequency excitation is that it promises independent control of the ion flux and the ion energy. In some circumstances, a third frequency is added to further control the etching processes by modifying the ion energy distribution function at the substrate. In this paper, we focus on the consequences of multiple-frequency excitation on the electron heating mechanisms, and in turns on the plasma uniformity. We will discuss the collisionless and collisional electron heating mechanisms within rf sheaths, when they are driven by two frequencies. For typical discharge parameters, we find the result that the collisionless heating produced by the combination of two frequencies can be much larger than that of either acting alone. We will also address the issue of electromagnetic effects arising when the wavelength associated with the highest frequency becomes comparable to (or shorter than) the electrode size. In this situation, the electric field has two components, (i) the usual capacitive field perpendicular to the electrodes, (ii) and the inductive field, parallel to the electrode. The power deposited by the inductive field may be greater than the capacitive power. As in classical inductive discharges, the high frequency capacitive discharge experiences capacitive-to-inductive (E to H) transitions when the injected power, i.e. the voltage between the electrodes, is increased. Finally, both the capacitive and inductive powers are radially non-uniform, which can lead to severe problems of process uniformity.

Authors Index

Bold page numbers indicate the presenter