Plasma Science and Technology
Room 315 - Session PS2-ThM

Advanced Ion and Reactant Control II

Moderators: Dr. Suman Bhaumik, TEL Technology Center, America, LLC, **Dr. Mingmei Wang**, Lam Research Corporation

11:00am **PS2-ThM-13 Energy-Resolved Angular Distribution of Ions Impinging on Biased Electrode in Dual-Frequency Capacitively-Coupled Ar Plasma***, **Hirotaka Toyoda**,* Nagoya University, Japan **INVITED**

The ion angle distribution (IAD) on the biased electrode is one of the factors that determine the shape in high-aspect-ratio etching, and experimental insights into how the IAD varies with plasma parameters are extremely important as fundamental data for etching shape simulations. Therefore, we have developed a specially designed dual-frequency capacitively coupled plasma (CCP) source to measure the angular distribution of high-energy ions incident on the RF electrode. In this apparatus, particles are extracted from the plasma into a drift tube through a sampling orifice connected to the RF electrode, and after passing through the drift tube, they are detected by a microchannel plate (MCP) assembly with a fluorescent screen, offering angular resolution of less than 0.01 degrees. From Ar plasma experiment, it was revealed that the IAD consists of a intense Gaussian peak (angular width: <0.5°) and a weak tail component (angular width: >1°). The width of the main peak decreased with increasing LF power, indicating that sheath acceleration contributes to the narrowing of the angular width. To investigate the collision effect within the sheath in more detail, the pressure was varied while keeping the sheath thickness constant by controlling the plasma density. As a result, the width of the main peak deviated from the expected tendency at high pressure and high sheath voltage, suggesting that sheath collisions increase the angular width. To further investigate the behavior of ions within the sheath, energy-resolved IAD measurements were performed using the Time-of-Flight method. It is known that ions passing through an RF-oscillating sheath have an energy distribution from high to low energy, and similar results were obtained in our energy-resolved IAD measurements. Furthermore, the main peak width decreased with energy, and assuming that the width of the main peak is determined by the ion temperature and sheath acceleration energy, the ion temperature was found to be ~0.04 eV regardless of the ion energy. This indicates that the main peak is generated by high-energy collisionless-ions and low energy ions those experienced charge-exchange collisions without momentum transfer. The behavior of the tail component of the IAD was also investigated by varying pressure. With increasing pressure, a relative increase in the tail component was observed. Monte Carlo particle simulations within the sheath suggested that the tail component originates from small-angle scattering of background Ar neutral particles and Ar ions.

Acknowledgement

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11:30am **PS2-ThM-15 Tailored Voltage Waveforms in Inductively Coupled Plasmas for Cryogenic Etching using Ar/HF Gas Mixtures***, **Yifan Gui**, Yeon Geun Yook, Chenyao Huang, Mark J. Kushner,* University of Michigan, Ann Arbor

In microfabrication, fabricating high aspect ratio (HAR) dielectric features has relied on capacitively coupled plasma (CCP) reactors using fluorocarbon chemistries. In these systems, process parameters are tuned to optimize the production of C_xF_y fragments and ion energy distributions with the end goal of balancing polymer deposition and chemical sputtering to maintain profile control and etch rate. Inductively coupled plasmas (ICPs) have not been extensively used for dielectric etching due to the difficulty in controlling the fragmentation of the fluorocarbon gases. Cryogenic plasma etching of dielectrics typically uses HF based chemistries which rely on water-HF condensation and physisorption rather than the thickness and composition of the fluorocarbon polymer passivation layer. Consequently, the need to optimize C_xF_y dissociation is eliminated, which then makes ICPs more attractive for cryogenic etching systems. Decoupling plasma generation by the source power and ion acceleration by the bias power is also less difficult using ICPs.

In this presentation we discuss results from a computational investigation of the use of voltage waveform tailoring (VWT), specifically a rectangular bias (RB) waveform, in ICPs for cryogenic etching of dielectrics. RB waveforms generate a more mono-energetic ion energy distribution to the substrate compared to sinusoidal biases. This investigation was performed using, the Hybrid Plasma Equipment Model (HPEM), a modular simulator designed for low-pressure plasma systems. This study focuses on the evolution of incident fluxes and energy angular distributions (EADs) for electrons and ions onto wafers for ICPs operating at pressures of tens of mTorr with Ar/HF feed gas. We will discuss the impact of an expanded operational space (plasma source type, power/voltage scaling, and waveform) on the resulting EADs and flux uniformity across the wafer.

Work supported by Lam Research, Samsung Electronics and Department of Energy Office of Fusion Energy Sciences.

11:45am **PS2-ThM-16 Mechanisms of Si, SiCl, SiCl2, and Cl radical production and their role in isolated sidewall taper formation in pulsed Ar + Cl2 plasmas***, **V S Santosh K Kondeti**,* Princeton University Plasma Physics Lab*; Leonid Dorf, Zihao Ding, Geuntak Lee, Sonam D. Sherpa, Takumi Yanagawa, Leonid Belau,* Applied Materials Inc.*; Yevgeny Raitses,* Princeton University Plasma Physics Lab

In chlorine-based plasma etching of silicon, sidewall taper in isolated features originates from the deposition of chemical by-products, which is governed by the generation and transport of reactive radicals. In this work, we investigate the mechanisms of Si, SiCl, $SiCl_2$, and Cl radical production and decay in a pulsed inductively coupled Ar + Cl_2 plasma with a pulsed bias voltage using time-resolved laser induced fluorescence diagnostics. The measurements show that SiCl radicals are produced predominantly in the gas phase through electron-impact dissociation of higher silicon chlorides ($SiCl_x$, x = 2–4), with $SiCl_2$ acting as a key precursor species. In contrast, $SiCl_2$ is generated primarily at the wafer surface and chamber walls through ion-assisted processes and desorption. The measured Si radical dynamics indicate that Si atoms are produced in the gas phase and sputtering of the wafer. Cl radicals are produced by the dissociation of the precursor Cl_2 gas during the plasma on-phase. $SiCl_2$ and Cl radicals increase in density in the afterglow after turning of all power suggesting that $SiCl_2$ is formed by this reaction $SiCl + Cl_2 \rightarrow SiCl_2 + Cl$ in the afterglow, before all species decay in density. The observed radical dynamics demonstrate that sidewall taper is governed by the buildup and decay of depositing species with a large sticking coefficient such as Si/SiCl, which can be controlled through modulation of plasma pulsing parameters. These results provide a mechanistic framework corelating plasma-phase chemistry to feature profile evolution and offer pathways to minimize by-product deposition for improved anisotropic etching.

This work is supported by Applied Materials and a Cooperative Research and Development Agreement (CRADA) between the Princeton Plasma Physics Laboratory and Applied Materials through the U.S. Department of Energy (contract DE-AC02-09CH11466).

12:00pm **PS2-ThM-17 Control of Electron Angular Distributions onto Substrates Using Non-Sinusoidal Low Frequency Biases in Capacitively Coupled Plasmas***, **Max Kellermann-Stunt**, James Prager,* University of Michigan*; Josh Perry, Paul Melnik, Timothy Ziemba,* Eagle Harbor Technologies*; Mark J. Kushner,* University of Michigan

Independent control of ion and electron energy distributions onto plasma facing surfaces is an important challenge for high-aspect-ratio (HAR) semiconductor etching. In capacitively coupled plasmas (CCPs), ions are accelerated through the sheath toward the wafer with relatively narrow angular distributions, while electrons generally reach the wafer during limited portions of the radio frequency (RF) cycle and often have broader angular distributions. The difference between the ion energy angular distribution (IEAD) and electron energy angular distribution (EEAD) can contribute to asymmetric charging in HAR features, leading to notching, microtrenching and twisting. Non-sinusoidal bias waveforms are being developed to narrow, in in both energy and angle, IEADs delivered to the wafer. These voltage waveforms ideally have a short positive portion and longer, constant negative. portion. A desired consequence of this waveform is an electric-field reversal in and near the sheath that will accelerate electrons towards the wafer with narrow angular distribution and high energies.

In this work we have computationally investigated EEADs and IEADs onto biased substrates in a CCP using non-sinusoidal waveforms. The investigation was conducted using the Hybrid Plasma Equipment Model (HPEM). Comparisons are made to experimental measurements of ion and electron energy distributions onto the substrate using an RFEA (retarding field energy analyzer).The experimental system consists of a CCP powered on the top electrode at 60 MHz with the bottom pedestal electrode biased by the non-sinusoidal waveform at 400 kHz. Measurements and simulations were performed for pure argon and argon-molecular gas mixtures with pressures ranging from 3 mTorr – 20 mTorr. The HPEM code was modified to enable simulation of electron energy distributions using very low frequency biases.

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