Plasma Science and Technology
Room 201 ABCD W - Session PS3-TuA

Plasma Science Late Breaking Oral Session

Moderators: Phillipe Bezard, IMEC Belgium, **Sara Paolillo**, IMEC Belgium

5:00pm **PS3-TuA-12 Atomic Layer Etching of Silicon in Continuous Flow, Pulsed Bias Power Plasmas**, ***Vincent Donnelly***, *Jeremy Mettler, Qinzhen Hao, Mahmoud A. I. Elgarhy,* Dept .of Chem. and Biomolec. Eng, University of Houston*; Heejung Kim,* Semiconductor R&D Center, Samsung Electronics Co., Ltd., Republic of Korea*; Sang Ki Nam,* Mechatronics Research, Samsung Electronics Co., Ltd., Republic of Korea*; Song-Yung Kang,* Semiconductor R&D Center, Samsung Electronics Co., Ltd., Republic of Korea

Atomic layer etching (ALE) provides superior control of etching rate uniformity, but is unacceptably slow for many applications when compared to conventional etching processes. In plasma-assisted ALE required for anisotropic etching, one cycle starts with exposing the substrate to a reactive gas such as Cl_2 for Si or fluorocarbon species for SiO_2, forming an adsorbed layer. The reactive gas flow is turned off and the reactor is purged of this species, usually with an inert carrier gas such as Ar. A plasma is ignited in the inert gas and a substrate bias results in energetic ion bombardment to remove a product layer. The problem with this approach is that the purge step needs to be long enough to reduce the reactive gas to a low enough layer such that no further chemisorption occurs during the ion bombardment step. Otherwise, the self-limiting nature of ALE is compromised. Even with the highest purge gas flow rates, it is difficult to reduce this purge time to less than one second, due at least in part to uptake and release of reactive gases from the chamber walls. Here we take a different approach to plasma ALE. With a constant inductively-coupled plasma (ICP) power, a continuous flow of reactant gas (Cl_2) was maintained in a continuous high flow of Ar carrier gas. Etching occurred during periodic substrate bias power periods (-75 DC self-bias voltage) of 0.2s to 0.5s. Between non-ALE continuous etching at too high a Cl_2 partial pressure, and a rate approaching physical sputtering at too low a Cl_2 partial pressure, an "ALE window" was found at low Cl_2 partial pressures where the chlorination rate during 1s periods with no bias power formed a $SiCl_x$ layer that was sputtered away during the substrate bias period at a rate that was faster than the rate at which the surface could re-chlorinate. Under these conditions, an etching rate of ~0.2nm/cycle, or about 1 monolayer of Si was achieved. Optical emission spectroscopy and a simple Langmuir-Hinshelwood model were used to monitor SiCl desorption during the ALE cycles and provided further insights into the etching mechanism. This work was supported in part by Samsung Electronics (project code IO240308-09220-01).

5:15pm **PS3-TuA-13 Correlation of Optical Emission Spectroscopy Line Ratios with Deposition Rate and Refractive Index of Silicon Nitride Films in Plasma Enhanced Chemical Vapor Deposition**, ***Youngju Ko***, *Hyeonjin Choi, Jinmyeong Kim,* Sungkyunkwan University (SKKU), Republic of Korea*; Namgun Kim,* Samsung Electronics Co., Republic of Korea*; Heeyeop Chae,* Sungkyunkwan University (SKKU), Republic of Korea

Optical emission spectroscopy (OES) is common non-invasive method for monitoring plasma in semiconductor manufacturing and analyzes emitted light without disturbing the plasma. Quantitative understanding of plasma states from OES peak intensities is still challenging. In this work, the deposition rate and refractive index of silicon nitride (SiN_x) deposited using trisilylamine (TSA), NH_3 and N_2 gas were predicted using OES analysis in plasma enhanced chemical vapor deposition (PECVD). The four dominant peaks of 337 nm (N_2 second positive system), 391.2 nm (N_2^+ first negative system), 656 nm (H_α Balmer line), and 486 nm (H_β Balmer line) were selected, and the correlation between the deposition rate and intensity ratios of I_{N2^+}/I_{N2} and $I_{H\alpha}/I_{H\beta}$ was investigated. The I_{N2^+}/I_{N2} was found to be strongly correlated with the deposition rate with coefficient of determination (R^2) of 0.85 and mean absolute percentage error (MAPE) of 3.66%. This strong correlation is attributed to the fact that the ratio represents the variation of electron temperature, which increases molecular dissociation and ionization in plasma. However, the refractive index was poorly correlated with the I_{N2^+}/I_{N2} and $I_{H\alpha}/I_{H\beta}$ line ratios, and the intensity ratios of I_{NH}/I_{N2} and I_{SiH}/I_{N2} were suggested from 336 nm (NH), 414.2 nm (SiH), and 337 nm (N_2) peaks as indicators representing the relative radical density of NH and SiH radicals. These line ratios were derived because they have similar overlap of excitation cross sections with electron energy distribution function (EEDF) in typical inductively coupled plasmas (ICP). The derived I_{SiH}/I_{NH} ratio showed a strong correlation with the refractive index, as the atomic composition of N and Si in the film is directly influenced by NH and SiH radicals in plasmas. The refractive index with I_{NH}/I_{N2} and I_{SiH}/I_{N2} line ratios showed high accuracy with R^2 of 0.95 and MAPE of 0.27%. This work demonstrated that the OES intensity ratio proposed as I_{N2^+}/I_{N2} and I_{SiH}/I_{NH} can effectively predict deposition rate and refractive index in SiNx PECVD.

5:30pm **PS3-TuA-14 Particle-in-Cell Simulations of Low Pressure Magnetized Plasma**, ***Taaresh Taneja***, Applied Materials Inc.*; Shahid Rauf,* Applied Materials, Inc.*; Prashanth Kothnur,* Applied Materials Inc.

Low pressure magnetized plasmas (e.g., magnetrons) are widely used for metal deposition in the semiconductor industry. This study focuses on kinetic phenomena important in these plasma discharges. In particular, the generation and propagation of waves of electron and ion densities are studied. One-dimensional Particle-In-Cell (PIC) simulations with Monte Carlo Collisions (MCC) of argon plasma are used for this investigation. The simulations were conducted across a range of pressures (1–10 mTorr), ion masses (10 amu – 160 amu), and external magnetic field strengths (peak ranging from 200 G to 400 G) to explore the influence of these parameters on the plasma dynamics. The plasma was confined between a cathode and an anode, with a magnetic field applied perpendicular to the simulation axis that exponentially reduces from the cathode to the anode.

Distinct wave-like structures were observed propagating from the anode towards the cathode under various conditions. These waves exhibited clear dependence on the magnetic field strength and ion mass, suggesting a magnetically driven mechanism. Detailed analysis of the wave frequency and phase velocity revealed characteristics consistent with ion cyclotron waves, including their scaling with the ion cyclotron frequency and propagation behavior in magnetized plasmas. However, these ion and electron density waves are not found to be in perfect resonance with the ion cyclotron mode. The frequency was found to also scale inversely with the square root of the ion mass, suggesting ion acoustic wave contribution. Moreover, the wave amplitude was found to rise in the direction of propagation, suggesting a non-linear, oscillation growing mechanism. This change in amplitude was much more pronounced at higher pressures, such as 10 mTorr.

The identification and analysis of these waves provide insight into ion transport and energy redistribution in magnetized low-pressure discharges, which are critical to optimizing sputtering efficiency and uniformity in physical vapor deposition processes. The results demonstrate the capability of PIC-MCC simulations to capture kinetic and magnetic field-induced transport effects that are often very crudely approximated in fluid models. These findings contribute to a deeper understanding of plasma behavior in magnetron systems and may inform the design of more efficient and controlled deposition environments.

5:45pm **PS3-TuA-15 Effect of Nitrogen Addition on Electron Density and Uniformity Enhancement in Oxygen Plasma**, ***Yeongjae Jeong***, *Chin-Wook Chung,* Hanyang University, Korea

In oxygen plasmas, the formation of negative ions leads to a reduction in electron density at the discharge center and degrades the overall discharge uniformity. This study investigates the effects of adding small amounts of nitrogen to oxygen discharges, focusing on changes in electron density and spatial uniformity. Experiments were carried out in a 13.56 MHz inductively coupled plasma at 200 mTorr under varying nitrogen admixture ratios. The electron energy probability function (EEPF) was measured radially using an RF-compensated Langmuir probe. The results show that the addition of nitrogen increases the central electron density by up to 42% and improves discharge uniformity. This phenomenon is attributed to vibrational excitation of nitrogen molecules, which acts as a competing energy loss channel for low-energy electrons, thereby suppressing the formation of negative oxygen ions and reducing electron loss. In this study, we define a parameter termed electron retention efficiency to quantify this effect and analyze its correlation with electron density enhancement. The results indicate that higher electron retention efficiency leads to a more significant increase in electron density, demonstrating that minor nitrogen addition can be an effective method to control electron density and uniformity in oxygen plasmas.

Author Index

Bold page numbers indicate presenter