Plasma Science and Technology
Room 201 ABCD W - Session PS2-ThM
Plasma Sources

Moderators: David Boris, U.S. Naval Research Laboratory, **Necip Uner**, Middle East Technical University

11:00am **PS2-ThM-13 Controlled Electron-Enhanced Silicon Etching with H_2 Background Gas and Positive Sample Voltage***, **Sumaira Yasmeen**, Andrew Cavanagh,* University of Colorado at Boulder*; Harsono Simka,* Samsung Electronics*; Steven George,* University of Colorado at Boulder

Controlled electron-enhanced silicon etching can be achieved with H_2 background gas and positive sample voltage. Electrons impinged on the silicon surface at normal incidence at currents of ≥200 mA over surface areas of ~4 cm^2. The electron energy was ~140-240 eV defined by the grid bias on the hollow cathode plasma electron source and positive sample voltages. The H_2 pressures were <3 mTorr. The silicon etching for Si(100) and a-Si at room temperature was measured using in situ spectroscopic ellipsometry. The etched silicon thickness was linear versus time during electron-enhanced etching. The etch rates increased progressively with larger positive sample voltages (Figure 1). Si(100) etched slower than a-Si. For example, the etch rates were ~2.6 Å/min for crystalline Si(100) and 9.9 Å/min for a-Si under the same conditions at an incident electron energy of 140 eV with a positive sample voltage of +90V.

Without the positive sample voltage, the silicon etch rates were negligible. In addition, electron-enhanced Si etching was not accomplished using a D_2 background gas instead of a H_2 background gas. These results support the proposed mechanism for electron-enhanced Si etching, where H_2 produces H^- via dissociative electron attachment (DEA) according to $H_2 + e^- \text{-->} H_2^- \text{-->} H + H^-$. The positive voltage on the sample stage then pulls the H^- negative ions to the silicon sample to react with silicon to produce SiH_4 as an etch product (Figure 2). The low-energy electrons required for DEA are secondary electrons produced by the primary electrons impinging on the silicon surface.

The energy of secondary electrons from silicon peaks at ~2-3 eV and drops off rapidly at higher energies approaching 10 eV. The peak of the DEA cross section for H_2 is 3.75 eV. In comparison, the peak of the DEA cross section for D_2 is 14.0 eV. The D_2 background gas may not be effective for silicon etching because D^- is not produced by DEA, as the secondary electron energy from silicon is too low. These results demonstrate a new mechanism for controlled electron-enhanced silicon etching based on H_2 DEA from secondary electrons and H^- attraction to the positive sample voltage on the silicon sample.

11:15am **PS2-ThM-14 Exploring New Experimental Approach: Operando Plasma-XPS***, J. Trey Diulus,* NIST*; Ashley R. Head, Jorge Anibal Boscoboinik,* BNL*; **Andrei Kolmakov,*** NIST-Gaithersburg

Recent advancements in instrumentation have enabled X-ray photoelectron spectroscopy (XPS) measurements at (near-)ambient pressures, overcoming previous high vacuum limitations and allowing for the characterization of sample chemistries under realistic conditions. In our current work, we demonstrate the capabilities of an ambient pressure XPS (APXPS) setup for in-situ plasma environment measurements. This "plasma-XPS" technique enables the study of plasma-surface interactions in operando, rather than relying on traditional before-and-after analyses[1].

Plasma-XPS is particularly valuable for identifying short-living reaction intermediates crucial to understanding plasma-assisted surface processes in applications such as semiconductor nanomanufacturing, biomedical plasma technologies, and plasma remediation, etc. We first apply this technique to monitor real-time surface chemical changes on model metal and dielectric samples exposed to oxidizing and reducing plasmas. By correlating surface spectra with concurrent gas-phase XPS measurements and mass spectrometry of species generated during plasma exposure, we reveal the critical influence of plasma-induced chamber wall reactions and near-sample plasma potential on the interpretation of the plasma-XPS spectra[2].

Ultimately, our findings demonstrate that plasma-XPS provides comprehensive insights into both surface and gas-phase plasma chemistry, establishing it as a powerful and versatile tool for fundamental and applied plasma research. We also discuss potential enhancements and future directions to further advance the capabilities of plasma-XPS metrology.

References

[1] J.T. Diulus, A.E. Naclerio, J.A. Boscoboinik, A.R. Head, E. Strelcov, P.R. Kidambi, A. Kolmakov, The Journal of Physical Chemistry C, 128 (2024) 7591-7600.

[2] J.T. Diulus, A.R. Head, J.A. Boscoboinik, A. Kolmakov, arXiv preprint arXiv:.19303, (2025).

11:30am **PS2-ThM-15 University-Scale Extreme-Ultraviolet Lithography Source***, Jan Uhlig, **Max Miles,** Dren Qerimi, David Ruzic,* University of Illinois at Urbana Champaign

To elevate our laboratory's research capabilities in Extreme-Ultraviolet (EUV) photoresist development, we have engineered a university-scale EUV light source designed for lithography applications at a fraction of the cost of commercial EUV tools. This innovative system leverages a Neodymium-doped yttrium aluminum garnet (Nd:YAG) Laser-Produced Plasma (LPP) with a swappable Tin (Sn)-based target to generate EUV radiation, offering an economical alternative to the high-cost infrastructure typically required for EUV lithography. Departing from an earlier dual EUV Multilayer Mirror (MLM) configuration, the current setup employs direct EUV exposure facilitated by a 150 nm Zirconium (Zr)-based transmission filter to isolate the EUV spectrum with high efficiency. A broad-spectrum photodiode detector, tailored to EUV wavelengths, provides accurate dosimetry, and its measurements are corroborated through successful exposure of EUV-sensitive photoresist-coated wafers. Experimental investigations have explored a range of target materials, including pure Sn and Sn-doped ceramics (typically 5 at%), utilizing Spectraflux 100B (Lithium Metaborate/Lithium Tetraborate 80/20) as a foundational component. Optical Emission Spectroscopy (OES) serves as an auxiliary diagnostic tool, enabling real-time monitoring of the LPP characteristics. Optimization efforts have focused on critical parameters—laser power, beam focus, operating pressure, and target composition—to achieve precise dose control and maximize EUV output while simultaneously addressing debris mitigation, a persistent challenge in LPP systems. The results demonstrate reliable photoresist exposure with adjustable EUV dosage, positioning this system as a cost-effective yet powerful platform for academic research. Compared to multimillion-dollar commercial EUV tools, this setup provides an accessible means to explore novel EUV photoresist modifications, with ongoing projects targeting enhancements in line-edge roughness and reductions in the minimum dose required for full development. This affordable, university-scale tool thus bridges a critical gap, enabling advanced EUV lithography studies without the prohibitive expense of industrial-grade equipment.

11:45am **PS2-ThM-16 Understanding the Plasma in Dielectric Barrier Discharges for Plasma-Enhanced Spatial Atomic Layer Deposition***, **Ralph Houben**, Antoine Salden, Jente Wubs, Richard Engeln, Erwin Kessels, Julian Held, Bart Macco,* Eindhoven University of Technology, Netherlands

Plasma-enhanced atomic layer deposition (PE-ALD) has enriched the ALD field, with the non-equilibrium nature of the plasma allowing for the synthesis of novel materials, tuning of material properties, and deposition at low temperatures. Pivotal to advancing the field of PEALD has been the detailed understanding of the plasma chemistry, including the role of reactive species and ions in driving surface reactions.

However, many emerging application in green technologies, including photovoltaics, batteries, and catalysis, require high-throughput, large-area deposition methods. Batch (thermal) ALD has already proven itself in the field of passivation layers for solar cells, yet plasmas are not easily integrated into such batch ALD systems. Spatial ALD (SALD) offers a route to incorporate plasmas using dielectric barrier discharges (DBDs), operating at atmospheric pressure and over large areas. Yet, the properties of DBDs and their influence on ALD deposition remain far less understood compared to the well-studied conventional PEALD plasmas.

We demonstrate how the DBD is implemented in the SALD tool used for deposition. The SALD setup consists of a head with multiple parallel slits through which precursors and co-reactants flow, separated by inert gas. The DBD plasma is applied over one of these gas channels, enabling plasma-enhanced surface reactions in a spatially separated, continuous process. This approach allows us to combine the scalability of SALD with the enhanced reactivity of plasma species.

We furthermore present a systematic study of a DBD source that is currently being integrated on our spatial ALD tool. Using optical emission spectroscopy, we investigate the gas temperature in the afterglow of the N_2/O_2 plasma, finding temperatures between 310 and 400 K depending on input power, which is compatible with ALD processes. Additionally, broadband absorption spectroscopy is used to quantify reactive species including O_3 and NO_x radicals, as function of N_2/O_2 ratio and input power, finding ozone densities of 10^{15} cm^{-3}. This indicates that the reactive species flux can be finely tuned via gas composition. At low O_2 dilution, we have indications that atomic O can become an important radical species. Current work focuses on the influence of these different radical regimes on the deposition processes on our spatial ALD tool for various materials, and their properties.

To conclude, our work contributes to bridging the gap between DBD plasma physics and ALD chemistry for plasma-enhanced spatial ALD, providing a pathway toward optimizing plasma conditions for scalable, atmospheric-pressure ALD processes aimed at clean energy applications.

12:00pm **PS2-ThM-17 Investigation of Temporal, Spatial and Angular Evolution of High-Power Impulse Magnetron Sputtering with Positive Cathode Reversal***, **Tag Choi**, Zachary Jeckell, Sam Pickholtz, Matt Salek, Ricky Pickering, Aaron Hackett, Dren Qerimi, David Ruzic,* University of Illinois at Urbana-Champaign

High-Power Impulse Magnetron Sputtering (HiPIMS) is a Physical Vapor Deposition (PVD) technique that delivers sub-microsecond high power pulses, enhancing ionization rate, ion energy and its directionality. Furthermore, a positive cathode reversal feature has been added to enhance the deposition rate and control the ion energy. These HiPIMS capabilities contribute to notable improvements in film quality, including higher density, stronger substrate adhesion, and enhanced step coverage, making HiPIMS with positive cathode reversal well-suited for advanced thin-film applications. Among the many challenges in the semiconductor industry, achieving uniform and dense thin films remains a critical focus. Addressing this requires a deeper understanding of the underlying plasma behavior during deposition. Thus, this study utilizes a Plasma Sampling Mass Spectrometer (PSM) to investigate the temporal, spatial, and angular evolution of titanium HiPIMS plasma with positive cathode reversal. A custom-built, high-vacuum compatible magnetron was mounted on both linear and rotational actuators, enabling detailed exploration of ion behavior across different positions and angles. The system allows for 40–300 mm axial translation, 90 mm azimuthal movement, and up to 90° rotation. Key HiPIMS parameters—such as main pulse duration, peak current, delay time between the main and positive kick pulses, kick pulse length, and kick voltage—were systematically varied to assess their individual impact on plasma characteristics. Additionally, the study examines the controllability between gas and metal ions, exploring its potential for process optimization and application-specific tailoring.

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