Plasma Science and Technology
Room Ballroom BC - Session PS-ThP
Plasma Science and Technology Poster Session

PS-ThP-2 Dependence of MQW Sidewall Damage on Ion Incident Angle: Insights from Molecular Dynamics Simulations*, **Eun Koo Kim**, Hyun Woo Tak, Geun Young Yeom,* Sungkyunkwan University (SKKU), Republic of Korea

Micro-LED (uLED) technology is emerging as a next-generation display solution due to its high brightness, energy efficiency, and scalability. In uLEDs, multiple quantum wells (MQWs) serve as the primary light-emitting layers, and preserving their optical performance is critically dependent on minimizing sidewall damage. As the lateral dimensions of uLEDs continue to shrink, the increasing proportion of sidewall area makes it critical to control the damage that is inevitably introduced during plasma etching processes. Such damage leads to increased non-radiative recombination at the sidewalls, which in turn significantly degrades the external quantum efficiency of the device. [1]

Although several approaches such as sidewall passivation using various materials and post-treatment techniques [2], as well as atomic layer etching (ALE), have been proposed to mitigate this issue [3], a comprehensive understanding of how the ion incident angle affects MQW sidewall damage remains lacking.

In this study, we employ molecular dynamics (MD) simulations to investigate the angle-dependent characteristics of ion-induced sidewall damage in MQW structures. Specifically, the analysis is categorized into (1) physical damage induced solely by ion bombardment and (2) damage resulting from ion bombardment after reactive radical adsorption—simulating typical RIE and ALE conditions. The simulations are designed to quantitatively evaluate the extent of structural damage in terms of penetration depth, surface roughness, sputtering yield, and dislocation formation, as functions of ion incident angle, ion kinetic energy, and ion dose.

The results of this study provide atomistic insights into the mechanisms of ion angle-dependent sidewall damage of MQWs and offer valuable guidance for optimizing plasma etching processes in advanced uLED fabrication.

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PS-ThP-4 Atomic Layer Etching of GaN Micro Light-Emitting Diodes with Different Sidewall Slope*, **Yun Jae Park**[1], Geun Young Yeom, Hong Seong Gil, Jong Woo Hong,* Sungkyunkwan University (SKKU), Republic of Korea

GaN-based micro light-emitting diodes (µLEDs) are widely used in display technologies due to their high brightness and high endurance in harsh environment. However, during the reactive ion etching (RIE) process for device definition of GaN-based µLEDs, damage to the activation layer or sidewalls can significantly degrade the device's external quantum efficiency (EQE). To mitigate this, various methods, such as optimizing the etch process or conducting post-etch processes (passivation insulator deposition, annealing, wet etching), have been studied to remove the damaged layer. However, more precise damage control techniques are needed as device dimensions shrink.[1]

In this study, we propose combination of wet etching with a plasma-based anisotropic atomic layer etching (ALE) process to remove sidewall damage induced by ICP-RIE. Tetra methyl ammonium hydroxide (TMAH) wet etching, commonly used to remove the damaged layer and to improve the etch profile in GaN-based µLEDs, is dependent on the crystal orientation, causing changes in the sidewall angle during processing. We examined how well the optimized ALE process could be applied to remove remaining sidewall damage across various sidewall angles, which vary with TMAH treatment time. To analyze the effect of ALE, we observed changes in electrical and optical performance, confirming improvements in both EQE and I–V characteristics when sidewall damage was effectively eliminated. Furthermore, transmission electron microscopy (TEM) analysis revealed that the damaged lattice region near the sidewall had been removed, supporting the physical recovery observed through electrical characterization.[2]

This study shows that sidewall angle, etching, and surface treatment all play an important role in enhancing µLEDs performance. The results suggest that employing ALE to precisely control the sidewall can improve the efficiency of GaN-based devices.

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PS-ThP-5 Anomalous Behavior of Plasma Potential in a Planar Helical Resonator Discharge*, **Un Jae Jung**, Yeong Jae Jeong, Min Seok Kim, Chin Wook Chung,* Hanyang University, Republic of Korea

Since a helical resonator plasma source does not require a matching network, it enables high-efficiency discharges and is considered a promising next-generation plasma source. An anomalous increase in plasma potential is observed in a planar helical resonator. As the applied power increases from 10 to 50 W, the plasma potential first increases and then shows a decreasing trend, similar to the E-to-H mode transition observed in inductively coupled plasmas (ICPs). Interestingly, as the power is further increased to approximately 400 W, the plasma potential increases again. The abnormal increase in plasma potential observed at high power disappears when a Faraday shield is inserted between the antenna and the plasma. This behavior is attributed to the significant amplification of the helical antenna voltage caused by resonance. These findings provide insight into themechanism of plasma potential formation in planar helical resonator discharges and the role of antenna–plasma coupling.

PS-ThP-6 Low-damage Atomic Layer Etching process for GaN-based Light Emitting Diodes*, **Chan Ho Kim**, Jong Woo Hong, Geun Young Yeom,* Sungkyunkwan University (SKKU), Republic of Korea

Today, due to its wide direct bandgap and high efficiency, Gallium Nitride (GaN) based devices have gained significant attention in various applications such as light-emitting diodes (LEDs) and power semiconductors. As the critical dimension of LED devices becomes smaller, reactive ion etching (RIE) process is widely used to fabricate GaN based devices to achieve anisotropic profile. However, ion bombardment during RIE process causes surface damage, which deteriorates GaN based LED device performance. This problem becomes more significant as critical dimension of LED device becomes smaller due to the higher ratio of sidewall area to total area.

In this study, atomic layer etching (ALE) process is introduced after RIE process to remove damage caused by RIE process in GaN based structure, including multi-quantum well (MQW) layer composed of InGaN and GaN. In TEM images, the MQW layer appeared indistinct after RIE process. Although wet etching followed by RIE improved layer visibility to some degree compared to RIE process, ALE process made the MQW layer more clear than wet etched MQW, indicating more appropriate damage removal. X-ray photoelectron spectroscopy (XPS) analysis exhibited that RIE induced damage changed the atomic ratios of N/Ga and Ga/In relative to reference data. However, after ALE process followed by RIE, the atomic ratios were returned similar to the reference data, although wet etch process also slightly restored atomic ratios. Furthermore, like XPS analysis data, Raman spectroscopy revealed that ALE process removed damage more efficiently compared to wet etch. Photoluminescence (PL) measurements at the same area showed that, as device size decreased, the damage caused by RIE is worse. However, PL intensity improvement was observed after ALE treatment and, as device size is smaller, the improvement in PL intensity is higher. Therefore, compared to wet etch process after RIE, ALE offers superior surface damage removal, especially showing its effectiveness in smaller devices.

PS-ThP-7 Comparison of SiN_x/SiO_x contact hole etching between CF_4 and low global warming gas*, **Jun Won Jeong**, Geun Young Yeom, Jong Woo Hong,* Sungkyunkwan University (SKKU), Republic of Korea

Demands for thinner, lighter, and higher-resolution panels in digital devices such as mobile phones, TVs, and laptops has led to the evolution of display technology such as LTPS (Low-Temperature Polycrystalline Silicon) technology. [1-2] LTPS thin film transistor (TFT) uses the excimer laser

[1] **JVST Highlighted Poster**

annealing (ELA) for crystallizing amorphous silicon (a-Si) at lower temperatures, therefore, LTPS achieves significantly higher electron mobility than conventional a-Si. [3] In the device processing for next-generation LTPS TFT, optimizing the SiNx/SiOx stack contact hole dry etching process is critical. This requires high SiN_x/SiO_x stack etch rates, minimal sidewall damage, and anisotropic etch profiles, and, conventionally, CF_4 is generally used in the SiN_x/SiO_x stack contact hole etching. This study compares the conventional perfluorocarbon (PFC) CF_4 gas with low global warming potential gases in the dry etching of SiN_x/SiO_x stack contact holes.

By using low global warming potential gases instead of conventional CF_4 in the etching of SiN_x/SiO_x stack, little lower SiN_x/SiO_x etch rates compared to CF_4 were obtained, however, much similar etch selectivity between SiN_x and SiO_2 in addition to higher etch selectivity over photoresist could be observed. In addition, more anisotropic etch profiles of contact hole and the lack of microtrenching at the edge of contact hole could be obtained with low global warming gases. The etch mechanism could be confirmed by observing the plasma characteristics with OES and QMS, and by measuring the surface characteristics after etching with XPS.

Therefore, for the contact hole etch processing, it is believed to be possible to replace CF_4 having a high global warming potential with alternative low global warming gases with enhanced etch characteristics.

PS-ThP-8 Enhancing Etch Characteristics of MTJ using RF-Biased RIBE*, **Kyoung Chan Kim**, Yun Jong Jang, Hong Seong Gil, Woo Chang Park, Dae Yeon Ha, Su Jeong Yang, Geun Yeong Yeom,* Sungkyunkwan University, Korea

STT-MRAM is actively researched as a next-generation memory due to its non-volatility, fast operation, high stability, and ease of scaling, all of which are essential for high-performance computing and AI advancements. Materials such as CoFeB, Ru, MgO, etc. are used in the Magnetic Tunnel Junction (MTJ) layer for data storage in addition to CoPt and CoIr to enhance magnetization stability. A common etching method for these MTJ stack layers is Ar^+ Ion Beam Etching (IBE).However, the Ar^+ IBE process leads to MTJ etch by-products redepositing on the pattern sidewalls. Tilting the substrate during Ar^+ IBE is generally used to address this issue but does not fully resolve issues like shadow effects especially for recent high aspect ratio and small CD patterns. Previously, to address these issues, Reactive Ion Beam Etching (RIBE) has been investigated with reactive gases such as CO/NH_3 and Cl_2 to improve volatility of etch by-products. However, this can degrade the MTJ magnetization properties. RIBE process using H_2/NH_3 mixed gases has been also investigated to mitigate some of these issues.

This study aims to improve etching characteristics by using mainly physical etching with slight chemical assistance by RF-biasing. Ar gas is injected for physical etching while H_2/NH_3 mixed gas is injected on to the substrate for chemical effect. When RF power is applied to the substrate, the plasma of H_2/NH_3 mixed gas is discharged on the substrate and induces RF-Biased RIBE. SEM images were taken to analyze etch characteristics. TEM measurements were conducted to analyze the sidewall residues.

PS-ThP-9 Etch Characteristics of Ru-Pt Composite Using Halogen-Based Gases*, **Hyeong Joon Eoh**, Geun Young Yeom,* Sungkyunkwan University (SKKU), Republic of Korea

The lithography process is a key step in patterning, and it is one of the most challenging processes in the introduction of high-resolution semiconductor manufacturing. To overcome this challenge, advancements in photolithography technology have been progressing in the direction of utilizing shorter wavelength light sources. This has led to the development of Extreme Ultraviolet Lithography (EUVL), which is now used in a few nm processes. High-NA EUVL is a further refinement of this technology, enabling stable patterning even at sub-2 nm processes. As the photomask for EUVL, reflective mask containing patterned EUV absorbing layer is used. TaN-based EUV absorber is generally used as an EUV mask absorber but, for High-NA EUV systems, a new EUV mask absorbing layer is known to be required to reduce image distortion, which degrades pattern quality. Ru–Pt composite is a strong candidate to replace the TaN-based absorber, considering the above conditions. In this study, the etch characteristics of the Ru–Pt composite are examined using halogen-based plasmas. The Ru/Pt composition ratio was varied, and the corresponding etch characteristics were investigated.

When etching the Ru–Pt composite using fluorine-based gas in an ICP system, the etch rate increased with increasing Ru content in the Ru-Pt composite. In contrast, under chlorine-based gas chemistry, the etch rate increased with increasing Pt content in the Ru–Pt composite. In the case of pure Ar+ ion sputtering without halogen gases, the etch rate increased with increasing Ru content in the composition. The effects of various process conditions on the etch characteristics of Ru-Pt composite required for EUV mask will be shown in the presentation.

PS-ThP-11 Isotropic Atomic Layer Etching of MoS_2 using Oxygen Plasma and Organic Solvent Vapor*, **Sunjae Jeong**, Hyewon Han, Jieun Kang, Jimin Kim, Geunyoung Yeom,* Sungkyunkwan University (SKKU), Republic of Korea

Preciselayer control of two-dimensional transition metal dichalcogenides (TMDs) is essential for the implementation of high performance electronic and optoelectronic devices. Atomic layer etching (ALE), which allows for precise layer control, can be performed using either thermal or plasma-based methods, enabling uniform etching. While conventional anisotropic etching has primarily been carried out through radical adsorption followed by ion-induced desorption, the increasing complexity of three-dimensional semiconductor device structures has led to a growing demand for isotropic etching techniques.

In this study, we utilize a method in which reactive radicals are generated through oxygen plasma and adsorbed onto the MoS_2 surface, followed by exposure to organic solvent vapor to facilitate the desorption of individual layers, thereby enabling precise layer control. Compared to conventional etching methods, this approach allows for damage-free processing while significantly improving the uniformity and precision of layer removal. Additionally, we compare the etching performance based on the chemical structure of the organic solvent vapor and the process temperature, emphasizing differences in reactivity and volatility during the etching process. These are important parameters in determining the efficiency and selectivity of the etching process. Our results confirm that the MoS_2 layers can be etched using a controlled manner, with approximately one monolayer removed per cycle, as verified through Raman spectroscopy and atomic force microscopy (AFM) analysis.

By achieving precise layer control of MoS_2, this study represents a significant advancement in the integration of TMD materials into next-generation electronic and optoelectronic devices. The findings contribute to the broader field of advanced materials research, paving the way for improved manufacturing techniques that meet the demands of future semiconductor technologies.

PS-ThP-12 Anticathode Effect on Multimodal Azimuthal Oscillations in Electron Beam Generated ExB Plasma*, **Nirbhav Chopra**,* Applied Materials,Varian Semiconductor Equipment*; Yevgeny Raitses,* Princeton Plasma Physics Laboratory

Electron beam (e-beam) generated plasmas with applied crossed electric and magnetic (ExB) fields are promising for low-damage (gentle) material processing [1]. However, these plasmas can be subject to the formation of plasma non-uniformities propagating in the ExBdirection. These rotating plasma structures (or 'spokes') enhance the transport of electrons and ions across the magnetic field, which can harm the gentle processing capability of plasma. In this work [2], we investigate the role of electrostatically active boundaries on the spoke formation by incorporating a variable bias conducting boundary (known as an anticathode) placed on the axially opposite side of the cathode. Our findings indicate suppression of azimuthal modes occurs when the anticathode is electron collecting. Furthermore, we show the highest frequency azimuthal mode is selectively suppressed by biasing the anticathode to an intermediate potential between the cathode and anode potentials. These findings suggest a link between the axial electron confinement in the e-beam generated plasma and azimuthally propagating plasma structure formation.

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PS-ThP-13 Plasmonic Plasma Process for Room Temperature Growth of Ultra-Thin Dielectric Films*, **Takeshi Kitajima**, Machiko Miyake, Toshiki Nakano,* National Defense Academy, Japan

Catalytic surface reactions utilizing gold nanoparticle plasmons have been utilized in various applications in recent years.[1] We have applied hot electrons supplied from gold nanoparticles to plasma surface reactions to use them to form high-quality ultrathin films at room temperature.[2] We focused on the mixed effect of visible light for plasmon excitation and plasma VUV emission and discovered the effect of green light excitation that promotes radical nitriding. Due to the mercury probe measurement and TEM imaging, the film grown have sperior dielectric feature and uniformity with less plasma induced damage in spite of nonuniform formation of gold nanoparticles.In the growth sequence, Au was vapor-deposited on a $SiO_2/Si(100)$ substrate in an ultra-high vacuum chamber with an average thickness of 0.4 nm by electron beam deposition to form Au nanoparticles (C) on the surface. A 30 mTorr N_2-inductively coupled plasma was generated in the attached chamber, and the sample was irradiated with N radicals (R) that passed through a 30 line/inch SUS304 single mesh with the configuration shown in Fig.1(a) for 5 minutes. A filter and a white LED controlled the wavelength of light (L), and VUV light from N_2 plasma was mixed. The reaction condition consisting of the above is RLC. Fig.1(b) shows the dielectric characteristics of the SiON film {leakage current and EOT (equivalent oxide film thickness) when 1 V is applied}. In green light suitable for Au plasmons, the hot electrons (~ 4 eV) generated by the deexcitation of plasmons enabled the bond conversion from Si-O to Si-N the ultra-thin SiON shows the same characteristics as the thermal oxide film. By mixing VUV, it is possible to increase the film thickness further and reduce leakage. Cross-sectional TEM image of SiON film after plasmonic process is shown in Fig.1(c). Beneath the Au particle SiON film with wide range of uniformity is confirmed and the single crystal lattice of Si substrate is clearly identified. Mixture of Au atoms into the dielectric film is examined with EDX spectrum shown in Fig.1(d). Au peak at 2.121 keV and 9.712 keV are less than the detection limit. From the above, it is considered that the reaction between the adsorbed N radicals and Si proceeded, and a good quality SiON film was formed by superimposing the photoelectron emission from the VUV light on the hot electron injection from the Au nanoparticles by green light irradiation.1 C. Clavero, Nat. Photonics 8, 95 (2014).2 T. Kitajima, M. Miyake, K. Honda, and T. Nakano, J. Appl. Phys. 127, 243302 (2020).

PS-ThP-14 Interaction of Sapphire (Single-Crystal Al_2O_3) and Ni-Based Alloy Surfaces with Halogen-Containing Plasmas and Gases

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In semiconductor manufacturing processes such as dry etching or chemical vapor deposition, capacitance manometers are widely used as essential vacuum pressure sensors to monitor and control the pressures of process gases. These gauges must be corrosion-resistant against process gases such as halides and their radicals generated by the plasmas. The diaphragm material of the manometer is especially important because, if its surface is altered by such corrosive gases, the sensor would send imprecise output signals possibly with the zero-point drift or pressure sensitivity shift. The errors are caused by the changes in mechanical properties of the diaphragm arising from the formation of the modified surface layer. For this reason, Ni-based alloys or polycrystalline ceramics of aluminum oxide (Al_2O_3) are typically used as the diaphragm material of capacitance manometers. More recent capacitance manometers employ sapphire (single-crystal α-Al_2O_3) as their diaphragm material, which is of specific interest in this study[1]. Recent studies on the interactions of polycrystalline Al_2O_3 with fluorine-containing plasmas indicated the formation of aluminum fluoride layers on Al_2O_3 exposed to such plasmas[2,3,4,5,6]. We have reported the results of ion beam experiments to understand the surface modification mechanisms of Ni-based alloys and polycrystalline Al_2O_3 film by fluorine-containing plasmas[7]. In this study, similar ion beam experiments with sapphire substrates have been executed to compare the surfaces of single-crystal Al_2O_3 and polycrystalline Al_2O_3. In addition, Ni-based alloy samples were exposed to xenon difluoride (XeF_2) gases for 1,3,6, and 12 months, and their fluorinated surfaces were analyzed and compared with the sapphire surfaces under the same conditions reported previously[7].

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PS-ThP-15 3D Feature Profile Simulation with Realistic Plasma Chemistry for High Aspect Ratio Etching in the Memory Industry

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The memory industry has faced drastic challenges in high aspect ratio etching processes consisting of ON stacks ($SiO2/SiN$) or SiO2 to achieve higher cell densities or cell capacities. Recently, the problems encountered in HAR etching processes are mainly due to abnormal profiles such as necking, bowing, random distortion. Despite these difficulties, current process development is still largely based on trial and error due to the inherent complexities of plasma physics and chemistry and plasma-surface interactions. To address this issue, we have developed a 3D feature profile simulation platform called K-SPEED, which includes a zero-D reactor simulation, a multi-level set algorithm, a ballistic transport algorithm and a surface reaction model. The accuracy of this approach has been verified by the intensive comparative study of experimental evidence. In this work, we investigated the origin of abnormal profiles using realistic 3D feature profile simulation along with key process conditions. We believe that our process simulation platform will significantly help to optimise the HAR process for the next generation of memory devices.

PS-ThP-16 Plasma Anodization for the Production of AlF_3 Layers

***Scott Walton**,* Naval Research Laboratory*; Javier del Hoyo,* NASA*; Michael Johnson,* Naval Research Laboratory*; Luis Rodriguez de Marcos,* NASA*; Makenzie Meyer, John Murphy,* Naval Research Laboratory*; Manuel Quijada,* NASA*; Maria Sales, Virginia Wheeler, David Boris,* Naval Research Laboratory

Efficient ultraviolet (UV) mirrors are essential components in space observatories for UV astronomy. Aluminum mirrors with fluoride-based protective layers are commonly the baseline UV coating technology; these mirrors have been proven to be stable, reliable, and have a long flight heritage. However, despite their acceptable optical performance, it is still insufficient for future large telescopes in which several reflections are required. Recently, a readily scalable, plasma-based passivation process was developed to produce a thin AlF3 layer on the surface of aluminum. The passivation process uses an electron beam generated plasma produced in a fluorine-containing background (SF_6 or NF_3), to simultaneously remove the native oxide layer while promoting the formation of an AlF_3 layer with a tunable thickness. This process has the characteristics of established aluminum anodization approaches – either electrochemical or plasma – except here, fluorine replaces oxygen as the reactant. The process takes advantage of the ability of electron beam driven plasmas produced in electronegative gas backgrounds to generate substantial densities of negative ions, which can be delivered to the surface and utilized to grow the fluoride layer. While layer thickness scales with applied bias as expected, the growth rates are challenging to understand. In this presentation, we will discuss the process using operating parameter studies, plasma diagnostics, and materials characterization, with an eye on understanding the growth mechanisms and the potential for better process control. This work is supported by the Naval Research Laboratory base program and NASA grant no. NNH20ZDA001N/20APRA200093.

PS-ThP-18 Experimental Investigation of the Interactions between Piezoelectric Crystals and Plasma Discharges

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Direct piezoelectric effect of non-centrosymmetric crystals, such as lithium niobate (LN) and lead zirconate titanate (PZT), provides opportunities to develop energy conversion plasma sources that remedy the need for high-voltage power supplies by directly transforming mechanical energy into plasma generation. To date, insight into the fundamental interactions and coupled physics between piezoelectric materials and plasma behaviors remains in its early stages. In this work, we utilized LN and PZT piezoelectric transformers (PTs) as model systems to investigate whether the level of the mechanically induced polarization in a piezoelectric crystal appreciably alters the behavior of a pulsed helium plasma jet impinging upon its surface, and whether these interactions manifest themselves in electrical characteristics. Preliminary optical and electrical characterization revealed that the morphology of the plasma jet plume and its contact at the plasma-crystal interface varied when the plasma jet generation was synchronized to different phases (i.e., different levels of polarization) of the input voltage to the PT. While no appreciable difference was observed in the plasma jet current, the current through the PT exhibited obvious suppression by the plasma jet, with the degree of suppression depending on the phase synchronization. Future studies will aim to achieve a more comprehensive understanding of these phenomena using time-resolved imaging technology and to determine if the dominant plasma properties, such as electron density and electron temperature, are also sensitive to the changes in polarization. Experimental findings from this work will be compared with simulation results, assisting in the development of a multi-dimensional, pizeo-plasma coupled model.

PS-ThP-19 Tailoring of Pulse Voltage Waveform for Monoenergetic Ion Energy Distributions*, **Seokhyeon Ha**, Hyeonho Nahm, Minseok Kim, Heejae Yang, Chin-Wook Chung,* Hanyang University, Korea

Tailored voltage waveform on DC-pulsed bias has recently attracted interest as an effective means to control ion energy distribution functions (IEDFs). As the ion density increases, ion charging on the substrate increases, leading to a broadening of the IEDFs. For more advanced control of the IEDFs, a feedback system between the ion density and the applied voltage waveform is developed. To tailor the voltage waveform based on the measured ion density, a real-time ion density monitoring system is required. We employed a floating harmonic probe to measure the ion density in real time. Using the measured ion density, the slope of the voltage waveform is determined. This enables the IEDFs to remain narrow at various conditions

PS-ThP-21 Plasma-Assisted Uptake and Thermal Removal of Hydrogen in Liquid Lithium for Hydrogen Storage Applications*, **Braden Moore,*** University of Illinois at Urbana Champaign*; Daniel O'Dea,* University of Illinois at Urbana Champaign, UK*; Meenakshee Sharma,* University of Illinois at Urbana-Champaign, India*; Elliot Sherman, Zach Nordan, Loren Calleri, Riley Trendler, David Ruzic,* University of Illinois at Urbana Champaign

Lithium hydride is a potential material for reversible hydrogen storage applications due to its high hydrogen content and energy density. Metal hydrides, in general, enable high mass density storage of hydrogen at low pressures and moderate temperatures, making them attractive for integration into future energy systems. While solid-state metal hydrides have been studied for this purpose, hydrogen uptake in liquid lithium for energy storage applications remains relatively underexplored. Hydrogen production through industrial-scale electrolysis or thermochemical splitting often involves high-temperature systems that could inherently maintain lithium in its molten state during hydrogenation. The University of Illinois at Urbana-Champaign (UIUC) has constructed the Actively Pumped Open-Surface Lithium LOop (APOLLO), which consists of a flowing lithium loop, a lithium free-surface, a hydrogen plasma source, and a distillation column for the thermal extraction of hydrogen. The flowing liquid lithium surface can be exposed to an Electron Cyclotron Resonance (ECR) hydrogen plasma source that has been characterized with an array of 16 Langmuir probes, a Retarding Field Energy Analyzer (RFEA), and actinometric spectroscopy. The hydrogenated liquid lithium then flows to an inductively heated Hydrogen Distillation Experiment (HyDE), which thermally treats the lithium at temperatures above 700°C to remove hydrogen. This presentation will focus on preliminary measurements of hydrogen uptake and removal at very low hydrogen concentrations. Future work will expand to higher hydrogen concentrations that are more applicable for an efficient energy storage system.

PS-ThP-22 Digital Twin Plasma Model for ICP Reactors: Integrated Multi-Physics and ML-Driven Optimization*, **Muhammad Abdelghany**[1],* Illinois Plasma Institute, University of Illinois at Urbana-Champaign*; Zachariah Ngan,* Department of Nuclear Engineering, University of California at Berkeley*; Dren Qerimi,* Illinois Plasma Institute, University of Illinois at Urbana-Champaign

Inductively Coupled Plasma (ICP) reactors are pivotal tools in modern semiconductor manufacturing, enabling high-precision etching and deposition processes essential for advanced device fabrication. Despite their widespread use, optimizing ICP reactor performance is challenging due to complex multi-physics interactions and the sensitivity of operating parameters, including RF power, frequency, gas composition, pressure, flow rates, and chamber geometry, as well as intricate plasma–surface interactions. We introduce a Digital Twin Plasma Model (DTPM) of an industry-grade ICP reactor that integrates multi-physics simulations, encompassing electromagnetic field computation, plasma kinetics, electron energy distribution, gas-phase chemistry, ion transport, and surface reaction kinetics, into a self-consistent framework. This high-fidelity model combines advanced physical models with machine learning-based predictive algorithms, providing a virtual replica of the reactor's plasma behavior.

The DTPM is implemented using a modular Python-based framework that defines the reactor geometry and plasma parameters and integrates an electromagnetic solver for computing inductive power coupling alongside a particle-in-cell (PIC) model for predicting ion density, electron temperature, and reactive species transport. Surface boundary conditions are incorporated to capture plasma–surface interactions on reactor walls and wafers. Ongoing validation uses a virtual probe to extract local electron temperature and plasma density, with a focus on capturing transient phenomena and non-uniform plasma distributions. To reflect the experimentally observed center-to-edge gradients, a 1D spatial resolution and a virtual Langmuir probe were incorporated into the kinetics solver, enabling direct comparison with experimental measurements. Preliminary results show qualitative agreement, indicating that the DTPM successfully reproduces these key features. In addition to physics-based simulations, the DTPM integrates machine learning (ML) techniques to enable surrogate modeling and real-time optimization. A data-driven surrogate model is trained on the simulation data, providing rapid predictions of plasma metrics as a function of control inputs. This ML-enhanced component accelerates parameter studies and supports on-the-fly optimization of operating conditions. By combining first-principles plasma modeling with ML-driven optimization, this digital twin approach paves the way for more efficient and adaptive control of next-generation industrial ICP systems in semiconductor production.

PS-ThP-23 Ion & Electron Energy Control with High Voltage Tailored Bias Waveforms in a CCP*, **James Prager**, Paul Melnik, Josh Perry, Chris Bowman, Timothy Ziemba, Kenneth E. Miller,* EHT Semi

The demand for solid-state non-volatile memory storage has increased the importance of plasma etching for producing high aspect ratio (HAR) features. To minimize defects in HAR features, precise control of the ion energy distribution function (IED) is essential. Additionally, controlling the electron energy distribution function (EED) is crucial to prevent positive charge buildup, which can distort etched features. EHT Semi has developed a high-voltage bipolar pulse generator that operates at 400 kHz. This system generates negative bias voltage waveforms that are flatter than those produced by standard sinusoidal radio-frequency generators, enhancing control over IEDs and process stability.

EHT conducted both experimental and computational studies to understand the interaction between bias waveforms and plasma properties. Using the bipolar pulser with a capacitively coupled RF plasma source, ion and electron energy distributions were measured with a retarding field energy analyzer (RFEA) at bias voltages up to 1.5 kV. Argon/oxygen plasmas were briefly investigated. The hybrid plasma equipment model (HPEM) code was employed to create a computational analogue of the CCP chamber, further elucidating the system's capabilities.

PS-ThP-24 An RF Generator Driving an Inductively Coupled Plasma Source Without a Matching Network*, **Timothy Ziemba**, Chris Bowman, Paul Melnik, Josh Perry, Connor Liston, James Prager, Kenneth E. Miller,* EHT Semi

Inductively coupled plasma (ICP) sources are used throughout the semiconductor and thin film industries. ICPs are driven by a radio frequency (RF) generator that is impedance matched to the plasma. However, matching networks increase the cost, complexity, and thermal management requirements of ICPs, which all scale with power of the RF generator. Additionally, the breakdown is often unreliable and takes a significant amount of time.

EHT Semi has developed a new RF generator that eliminates the need for a matching network. This RF generator is being tested on ICPs across a range of experimental parameters (power, neutral pressure, and gases). EHT will present results on breakdown time and reliability compared to traditional RF generators with a matching network. The generator response to plasma impedance changes and constant and variable power will also be presented.

PS-ThP-25 Investigation of Ion Flux/Sidewall Interactions in High Aspect Ratio (HAR) Features*, **Tanjina Akter**, David S. Kanfer, Steven Shannon,* North Carolina State University

Ion interaction with vertical sidewalls in high aspect ratio etching plays a critical role in the etch profile of features in advanced memory devices. Feature distortions such as notching, bowing, and footing can occur due to deposition, sputtering, or charge accumulation brought about by ion interaction with these sidewalls. Charge accumulation is one of these interaction types that contribute to profile distortion. Simulations have

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been conducted to spatially map this charge buildup, however, there is no diagnostic to provide experimental validation of this accumulation of charge. A novel diagnostic probe has been developed to measure the surface charge distribution inside the HAR features. The probe consists of an array of 10:1 aspect ratio vias (100 nm diameter) on PECVD Oxide with an aluminum ring encircling each via at varying heights. Voltage pickups from the aluminum rings enable the interpretation of a charge profile within the feature through differential measurement of voltage from an adjacent ring where the etched via is absent. This paper presents preliminary characterization of the ion particle flux and ion energy flux for an experimental CCP reactor that will be used to test this probe. A dual RF bias configuration with high (65 MHz) and low frequency (13.56 MHz) bias on each electrode has been employed to better control the ion energies. The control of ion flux distribution through the manipulation of the driving RF waveform can aid in mitigating charge-induced distortions and optimizing plasma processing for HAR structures. The IEDF was obtained by putting an RFEA on the lower-frequency electrode. Bimodal IEDFs were found for the pressure range of 1-100 mTorr, electron densities of 10^9 - 10^{11} cm^{-3}, and sheath potential of 50-1000 V using argon gas. The voltage at the top and bottom aluminum rings of a HAR via at the probe are calculated to be ~400 mV and ~100 mV respectively for the electron density of 10^{10} cm^{-3} and electron temperature of 4 eV, indicating that the design will have sufficient measurement resolution to measure these charge distributions.

This work is supported by the Department of Energy Office of Fusion Energy Sciences (DOE OFES Grant DE-SC0024545).

PS-ThP-26 Real Time Plasma Temperature Profiling Using Short Wave Infrared Imaging*, **Logan Holler**, Drhuval Patel, Qerimi Dren, David Ruzic,* University of Illinois at Urbana-Champaign*; Michael Stowell,* Lyten

Recent research has increasingly focused on the growth of graphene within atmospheric pressure plasmas. While it is well established that graphene formation is highly temperature-dependent, the distinction between the formation of graphene flakes versus nodules remains insufficiently characterized within plasmas. A key step forward centers on better mapping the temperatures across our different plasma mixtures. However, conventional diagnostic tools often fall short: most diagnostic systems only provide one-dimensional snapshots, and physical probes degrade rapidly under the high temperatures present in these environments.

To overcome these limitations, we propose the use of Short-Wave Infrared (SWIR) imaging as a nonintrusive method to obtain real-time, spatially-resolved temperature measurements across our plasma systems. SWIR imaging leverages blackbody radiation emissions to determine temperature by integrating spectral radiance over the detectable range of our camera. Provided that the camera's solid angle to the plasma remains fixed, changes in the integrated spectral intensity can be used to derive temperature ratios. By calibrating the system using a known temperature region within the plasma, we can correlate image intensity with absolute temperature for the same or similar plasmas by finding temperature ratios proportional to flux ratios. This allows for dynamic temperature mapping throughout the plasma, which is limited only to the refresh rate of the SWIR Camera.

Two methods are being developed to model and validate this approach. The first involves the insertion of a tungsten rod perpendicular to the flow of the plasma, which is incrementally raised through the plasma and allowed to reach thermal equilibrium at each position. This enables time-resolved images to determine temperature gradients and validate our current simulations. The second method involves varying gas mixtures to generate a calibration dataset, allowing the system to be adapted to different plasma environments. These experiments aim to correlate temperature regions with distinct graphene growth, such as flake versus nodule formation. Real-time, full-plasma monitoring also allows for characterizing how dynamic changes to the plasma occur, offering insight into the factors influencing graphene morphology.

PS-ThP-27 Monitoring Net CO_2 Dissociation Rates in the Effluent of Common Plasma Discharges with Optical Emission Spectroscopy*, **Andrew C Herschberg**, Nathan Bartlett, Jameson Crouse, Jaime Robertson, Emily Greene, David N Ruzic,* University of Illinois at Urbana-Champaign

Carbon dioxide is an important gas for many plasma discharges, among these include carbon capture and chemical conversion technologies. Such plasma-based systems offer increased sustainability by reducing net carbon footprints and limiting waste from industrial processes. During plasma excitation, much of the CO_2 present in the inlet flow will be reduced into CO or other products. Therefore, the CO_2 dissociation fraction can be used as a metric for extent of reaction and to optimize process efficiency. Many methods can be employed for this purpose; in this work, an OES method of interest is compared against a standard QMS measurement. These metrologies are implemented into the exhaust gas from a flowing inductively coupled plasma containingCO_2 and N_2. The OES method employs a self-actinometry technique, comparing the line ratios from the CO Angstrom and N_2 second positive spectroscopic systems. This is implemented through a Gencoa OPTIX Remote Spectrometer for a more direct comparison to a differentially pumped SRS Residual Gas Analyzer. Overall both methods were comparable, measuring similar dissociation fractions under tested parameters, with a maximum dissociation of approximately 90%. Actinometric constants for the OES method were stable, deviating by as little as 2% across tested conditions. Implementation of the OES self-actinometric method will require calibration on system of interest, but showed to be more consistent with lower error than the QMS method.

PS-ThP-28 Measurement and Modelling of Sn-H2 Vapor Diffusion Coefficients in the Transition Flow Regime*, **Jameson Crouse**, Nathan Bartlett, Emily Greene,* University of Illinois at Urbana-Champaign*; Shiva Rajavalu,* ASML*; Andrew Herschberg,* University of Illinois at Urbana-Champaign*; Sergio Ferraris, Niels Braaksma,* ASML*; David Ruzic,* University of Illinois at Urbana-Champaign

Extreme ultraviolet (EUV) lithography sources use tin in the process of generating 13.5nm wavelength light. Accurate modeling of neutral tin transport is important to understand how the tin coats different sections of the EUV source, which can reduce effectiveness. Modelling relies on knowledge of the diffusion coefficients of neutral tin vapor through molecular hydrogen. This work experimentally and numerically determined the diffusion coefficients of tin through molecular hydrogen at different tin temperatures and ambient pressures. Two experimental projects were used along with a CFD simulation and molecular dynamics simulation. For the most recent experiments, a known amount of tin is evaporated using an inductively heated crucible into a pipe with a known flow profile at a known ambient pressure. An OpenFOAM CFD model of the pipe is used to determine the flow profile within the pipe, along with the use of a diffusion model to predict tin transport. The pipe is inside of a large EUV source chamber prototype which can handle high hydrogen flows. Deposited tin is measured downstream of the pipe at varying distances with witness plates of different materials. Thickness measurements done with a profilometer are used to measure tin flux downstream of the Sn vapor source, which is then compared to the CFD model. Inertia and diffusion coefficients are adjusted in the model to match modelled fluxes to the experiment. A separate experiment is conducted utilizing mass loss measurements of a long crucible kept at a constant temperature and pressure over multiple hours, with tin evaporating out at a known rate. A variety of analytical and numerical coefficients were then compared to experimental fits of mass flux vs position to find the diffusion coefficient. Chapman-Enskog and Fick's law are the main analytical models utilized. A LAMMPS molecular dynamics model is also utilized to provide a wide array of results across the parameter space studied in this work, which is found to follow Chapman-Enskog theory well, even at lower pressures. The LAMMPS model uses mean squared displacement of Sn to calculate diffusion as the particles interact with H2 through a LennardJones potential. The results detail diffusion coefficients of tin in molecular hydrogen for varying temperatures, pressures, and hydrogen flow speeds with minimized error for each measurement and converging results between experiments."

PS-ThP-29 Simultaneous Deposition and Removal of Tin in a Hydrogen Plasma Environment*, **Nathan Bartlett**, Jameson Crouse, Andrew Herschberg, Emily Greene, Jaime Robertson, Jack Granat, Lucia Suarez Heredero, Matias Habib, Karl Vu, David Ruzic,* University of Illinois at Urbana-Champaign

Tin laser produced plasmas (LPPs) are used to generate 13.5 nm light in state-of-the-art extreme ultraviolet (EUV) lithography tools. Inside these tools, hydrogen gas is used as a buffer gas to decelerate ions from the LPP and is photoionized in the process creating a steady background hydrogen plasma. This plasma etches away tin as it accumulates on the wall of the EUV source forming the volatile compound stannane. Accurate etching rates of tin are needed to model tin accumulation inside of an EUV source. In this work, we present the results of a new experiment at the University of Illinois at Urbana-Champaign where tin vapor is simultaneously deposited and etched off of a substrate. In the experiment, a high temperature effusive source is used to deposit tin vapor onto a substrate while a hydrogen microwave plasma is used to generate hydrogen radicals and remove tin from the surface. Etch rates are presented as well as the morphology of tin accumulated onto the substrate surface. The experiment is simulated using a transport and surface chemistry model ran in the OpenFOAM framework. Results from the experiment are compared with the model and used to validate the model.

PS-ThP-30 Plasma Cleaning Performance and GWP Reduction Using ClF3 as an NF3 Alternative in Semiconductor Manufacturing*, Dong Ha Song, Sun Jae Jeong, Ga Hee Oh, Geun Young Yeom,* Sungkyunkwan University (SKKU), Republic of Korea

The effective removal of process residues from the chamber following Si-based deposition is critical for ensuring process uniformity and maintaining tool performance in semiconductor manufacturing. Nitrogen trifluoride (NF_3) has been widely adopted for this purpose, but its high global warming potential (GWP) presents increasing environmental concerns. In response, chlorine trifluoride (ClF_3), a highly reactive gas with significantly lower GWP, has emerged as a promising alternative [1].

In this work, we evaluated the cleaning performance of ClF_3 compared to NF_3 in plasma-enhanced environments, focusing on both etch rate and spatial uniformity across the chamber. Silicon dioxide and silicon nitride-coated wafers were strategically placed within the chamber to quantify residue removal efficiency under both gases. To further improve gas utilization, we introduced nitrogen (N_2) as a diluent and analyzed the impact of its partial pressure on cleaning effectiveness.

The experimental results demonstrate that introducing N_2 allows for a reduction in overall gas consumption while maintaining comparable etch performance. Moreover, ClF_3 not only offers environmental benefits but also delivers efficient cleaning across various chamber regions, making it a viable low-GWP alternative for next-generation plasma cleaning processes [2].

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PS-ThP-31 EUV PR Patterned SiON Etching with Enhanced Selectivity and LER Control Using Ion Beam Technique*, Yun Jong Jang, Hong Seong Gil, Kyoung Chan Kim, Woo Chang Park, Dae Yeon Ha, Geun Young Yeom,* Sungkyunkwan University (SKKU), Republic of Korea

As extreme ultra-violet (EUV) lithography advances toward sub-10 nm patterning, the etch challenges associated with thin, low-resistance EUV photoresists (PR) become increasingly critical. This study presents a novel ion beam etching approach employing a grid pulsing technique to enhance the etch selectivity and line edge roughness (LER) control for EUV PR-masked SiON structures. In the proposed method, Ar/H_2 plasma is generated in an inductively coupled plasma as a source chamber, while a fluorocarbon gas mixture (CF_4:C_4F_8) is injected into the downstream process chamber. Pulsing the grid voltages modulates the ion energy temporally, alternating between high-energy etching and low-energy fluorocarbon deposition phases.

We observed that decreasing the pulse duty ratio from 100% to 50% significantly increased SiON-to-EUV PR etch selectivity (approaching ∞) and reduced LER from 9.6 nm (continuous mode) to 6.1 nm, closely matching the unetched reference (5.8 nm). XPS and FTIR analyses showed increased fluorocarbon presence at lower duty ratios, correlating with reduced PR damage and improved LER while maintaining etch profile quality. Ion energy distribution measurements confirmed the alternating high/low-energy ion bombardment mechanism as key to balancing selectivity and LER.

These results highlight grid pulsing as a powerful, tunable method for precision etching in EUV-based semiconductor processing, offering new opportunities for sub-10 nm node integration with minimized pattern distortion.

PS-ThP-32 Reduction of Plasma-Induced Damage via Ultra-Low Electron Temperature Plasma in Gate-All-Around FET Fabrication*, Kim Hyungdong, Chung ChinWook, Nahm HyunHo, Ha Seokhyun,* Hanyang University, Korea

HfO_2 and TiN are representative materials used as gate oxides and metal gates in gate-all-around structures. However, damage caused by plasma during plasma processing has recently become a major concern due to its significant impact on device performance. In this paper, an ultra-low-electron-temperature (ULET) plasma (T_e < 1 eV) is applied to improve the etch characteristics of HfO_2 and TiN. The ULET plasma is generated using an inductively coupled plasma with a DC-biased grid. Results show that the ULET plasma reduces surface roughness by 33% for HfO_2 and 38% for TiN compared to conventional plasma. The residual concentration of fluorine decreases by 14% for HfO_2 and 58% for TiN, indicating an improvement in surface impurity levels. The improvements are attributed to the lower ion energy in ULET plasma, which suppresses ion bombardment damage. Our findings demonstrate that mitigating plasma ion damage to HfO_2 and TiN effectively prevents performance degradation and expands the process window in semiconductor manufacturing, and enables the implementation of more diverse device structures.

PS-ThP-33 Micro-Masking Effects in TCP–ICP RIE with Fluorine-Based Plasmas: Influence of Alumina and Quartz Dielectric Screens*, Giuseppe Libero Bufi, Pascual Muñoz, Daniel Pastor,* Universitat Politècnica de València UPV, Spain

Surface quality is a key factor in microelectronics and photonics fabrication, where even slight increases in roughness can degrade optical or electrical performance. During plasma etching, micro-masking can lead to surface roughening and the formation of particle-like features, which are generally undesirable for high-precision patterning.

In this study, we investigated unexpected surface roughening during the etching of silicon dioxide (SiO_2) and silicon nitride (SiN) films in a transformer-coupled inductively coupled plasma (TCP-ICP) reactive ion etching (RIE) system using CF_4 and CF_4/O_2 gases. Despite testing different combinations of chamber pressure, source power, substrate power, and gas flow ratios, the etched surfaces consistently exhibited nanometer-scale roughness and micro-masked features with an average area greater than 200 nm^2 per feature. Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) revealed the presence of aluminum and fluorine on the etched surfaces, with an Al:F atomic ratio of approximately 1:3.6, indicating that the deposited material is likely aluminum fluoride (AlF_3). A plausible mechanism involves fluorination of the alumina protective screen located beneath the quartz window, followed by ion-assisted sputtering and redeposition onto the wafer surface, where the low volatility of AlF_3 under these conditions leads to persistent micro-masking. The dielectric screen serves to shield the quartz window from direct plasma exposure but can thus become a source of redeposition.

To assess the role of reactor hardware on surface quality, the 1 mm-thick alumina screen was replaced with a quartz screen of similar geometry. A direct comparison using the same CF_4/O_2 etch recipe on unpatterned 300 nm SiN-on-Si wafers showed a significant improvement: atomic force microscopy (AFM) measurements revealed a root-mean-square roughness R_q of 5.25 nm with the alumina screen, reduced to 0.49 nm with the quartz screen, representing a tenfold improvement. SEM inspections further confirmed the elimination of micro-masked surface features with the quartz dielectric screen.

This investigation identified the source of the micro-masking, enabling a screen material change that significantly improved the etch process. Beyond providing a practical mitigation strategy, this study underlines the importance of considering hardware-induced micro-masking in the development of roughness-sensitive microelectronic and photonic fabrication processes.

PS-ThP-34 Computational Study of a Radio-Frequency Positive Ion Source for Neutral Beam Injectors*, Mohammad Sazzad Hossain, Amanda Lietz, Tom Regev, Arthur Mazzeo, Keanu Ammons, Florian Laggner, Miral Shah, Kirtan Davda, Steven Shannon,* North Carolina State University*; Evan Kallenberg, Brendan Crowley, Tim Scoville,* General Atomics

The Large, Uniform Plasma for Ionizing Neutrals (LUPIN) is a radio-frequency (RF) inductively coupled plasma (ICP) chamber designed to demonstrate and optimize a positive ion source upgrade for the neutral beam injection system on the DIII-D tokamak. LUPIN is designed to operate at up to 20 kW of RF power at 2 MHz, coupling energy through a cylindrical quartz vessel (20 cm in length, 10 cm radius) to achieve target ion current densities of 1500 A/m^2. This work presents fluid-kinetic modelling of a LUPIN H_2 plasma with parametric sweeps in RF power, pressure and frequency to study their impact on plasma chemistry, density, and ion flux at the grid. The effects of each operational parameter on plasma density, ion flux, and uniformity were investigated and the density was validated against experimental measurements. Increasing power shifts the primary ionization channel from molecular to atomic with diminishing flux increases due to skin–depth contraction and rarefaction, higher frequency localizes heating and raises H_2^+ and H_3^+ delivery to the grid, while elevated pressure boosts ionization yet degrades ion transport due to increase in collisionality.

This work is supported by US DOE under DE-SC0024523 and DE-FC02-04ER54698.

PS-ThP-35 Amorphous Carbon Deposition: Insights from Plasma Dynamics, Feature Scale Modeling, and Density Functional Theory, *Purva Paranjape,* Purdue University, USA*;* ***Kallol Bera,*** Applied Materials Inc.*; Rupali Sahu, Nakul Nuwal, Sathya Ganta, Prashant Kulshreshtha,* Applied Materials, Inc.

With advances in nanoelectronics, 3D integration of semiconductor devices has become essential. Amorphous carbon gapfill is critical for enabling vertical stacking. Plasma Enhanced Chemical Vapor Deposition (PECVD) is widely used to deposit these sacrificial layers. Achieving conformal, void-free deposition is vital for structural integrity. Partial gapfill studies help identify process conditions that yield such profiles. Hydrocarbon-based PECVD at intermediate pressures shows non-monotonic deposition behavior: decreasing then increasing with pressure. At lower pressures, films exhibit overhangs and high bottom deposition. At higher pressures, deposition becomes conformal and void-free.

To understand these mechanisms, we use a multi-scale modeling approach combining 1D plasma simulations, 3D feature-scale modeling, and Density Functional Theory (DFT). The plasma model includes continuity equations, drift-diffusion for electrons, ion momentum conservation, energy balance, and Poisson's equation. A particle model with collisions is used to calculate ion energy and angular distribution using electric fields from the plasma model. Feature-scale simulations use Monte Carlo methods to model particle transport, surface reactions, and profile evolution. DFT provides adsorption energies of plasma-generated species on carbon surfaces, revealing the relative importance of surface processes.

Simulations show that flux of dissociation-generated radicals decreases, while polymerization-generated radicals increase with pressure. Ion flux remains stable, but ion energy drops and angular spread broadens. At lower pressures, deposition is ion-assisted via dissociated radicals. At higher pressures, chemisorption of polymerized radicals dominates. DFT shows stronger adsorption of dissociated radicals. Feature-scale modeling reproduces experimental profiles, validating our multi-scale model. Directional ion-assisted deposition causes overhangs at low pressure; chemisorption leads to conformal films at high pressure. A pinch-off occurs at intermediate pressures due to competing mechanisms. Our study highlights the role of plasma-surface interactions due to ion flux, energy, angular distribution, and neutral fluxes in controlling feature profiles. The validated model helps identify optimal conditions for desired feature profiles.

PS-ThP-36 Spatiotemporal Analysis of a Submerged Water Plasma Driven with Nanosecond Long Voltage Pulses, *Michael Johnson, David Boris, Lina Petrova,* Naval Research Laboratory, USA*;* ***Mackenzie Meyer***[1]*,* National Research Council*; Scott Walton,* Naval Research Laboratory, USA

Atmospheric pressure plasmas generate a distinct chemical and electrical environment ideal for treating water, making them attractive for applications in wound healing, chemical synthesis, nanomaterial fabrication, and water remediation. These plasmas can operate in a nonequilibrium regime when driven by short pulses of power, lasting tens to hundreds of nanoseconds, that energize electrons but are too short to significantly heat the surrounding gas. This study investigates the impact of pulse width on plasma-water interactions by applying 70–350 ns pulses to an argon plasma submerged in water. Plasma properties are analyzed using optical emission spectroscopy and electrical measurements. Results indicate that within the first 15 ns of the pulse, the plasma fully fills the gap between the electrodes. After this initial stage, the plasma expands to occupy the entire inter-electrode space for the remainder of the pulse, forming an arc-like plasma where current flow is regulated by the power supply. Essentially, pulse width determines how long the plasma remains in this high-current state. Optical emission spectroscopy revealed that argon dominates the emission immediately after plasma formation, but over time, hydrogen emission becomes more prominent as the plasma dissociates water molecules. This results in higher power consumption at longer pulse widths due to increased energy transfer to the water. Spatial emission profiles show uniform hydrogen emission across the reactor, whereas argon emission weakens near the positive electrode. Significant broadening of emission lines was observed during the pulse, with Stark broadening of hydrogen lines used to estimate electron density. Measurements indicate that a substantial electron density persists for several microseconds after the pulse, likely due to residual voltage on the electrodes during power supply neutralization. At the longest tested pulse width (350 ns), the post-pulse current lasted nearly 10 µs, highlighting not only the influence of pulse width on plasma dynamics but also the importance of other system parameters in determining plasma lifetime.

This work was partially supported by the U.S. Naval Research Laboratory Base Program.

PS-ThP-37 Reliable Monitoring of Plasma Chamber Cleaning via a Newly Developed Endpoint Evaluation Sensor, *Suyoung Jang, Dohyeon Kim,* ***Kyongnam Kim,*** Daejeon University, Republic of Korea

This study presents the development and application of a Cleaning Endpoint Evaluation Sensor (CEES) to enhance monitoring accuracy and uniformity control during NF_3-based remote plasma cleaning in semiconductor equipment. Increasing chamber pressure increases fluorine radical density and improves etch reactivity, but cleaning non-uniformities persist, particularly in structurally constrained "dead volume" regions, such as the undersides of substrates, where reactive species cannot effectively reach. Conventional diagnostics, such as Optical Emission Spectroscopy (OES), lack the capability to verify cleaning completion in these challenging areas. In contrast, the CEES directly measures the removal of thin films that mimic actual process residues, providing real-time, spatially resolved endpoint evaluation. Experimental results demonstrate a strong correlation between CEES measurements and actual etch behavior, enabling the identification of regions where cleaning remains incomplete even when OES indicates completion. These findings highlight the potential of CEES as an effective tool for monitoring cleaning uniformity and determining the true endpoint of plasma-cleaning processes. Integration of CEES into advanced diagnostic platforms could significantly improve process reliability and efficiency in semiconductor manufacturing.

PS-ThP-38 Effect of H_2O Additionon Fluorocarbon Layer Formation on SiO_2 and Si_3N_4 Films inC_4F_8 Plasmas, ***Haegeon Jung****, Heeyeop Chae,* Sungkyunkwan University (SKKU), Republic of Korea

The effect of H_2O addition to C_4F_8/Ar plasmas on fluorocarbon (CxFy) layer formation was investigated on SiO_2 and Si_3N_4 films and compared with O2 addition. Tailoring of the fluorocarbon layer is a critical factor in achieving high selectivity and profile precision in high-aspect-ratio contact (HARC) etching. Etching was performed at 21 mTorr, 20°C, 30s, 130W source power, and no bias power.The fluorocarbon layer on SiO_2 was 26 nm in C_4F_8-only plasmas. O_2 addition reduced the thickness to 6 nm, and H_2O addition reduced it to 21 nm. The fluorocarbon layer on Si_3N_4 was 8.9nm in C_4F_8-only plasmas. O_2 addition decreased the thickness to 3.9nm, and H_2O addition increased it to 12.5nm. Oxide surface promotes carbon scavenging to CO/CO_2, and ion-assisted removal is strong, and the fluorocarbon layer on SiO_2 remains thin with bias [1,2]. Nitride surface lacks an efficient carbon-removal path to CO/CO_2, and NH_x/Si–F_x terminations increase CF_x retention, and ion bombardment cross-links and densifies the film, and the fluorocarbon layer on Si_3N_4 remains thick with bias [1,3]. SiO_2 surface provides polar sites that increase CF_x residence time and lower the nucleation barrier. CF_x nuclei survive more readily, and continuous-film formation is rapid. Interfacial Si–F_x formation depletes F and weakens F-driven thinning, and the layer on SiO_2 becomes thick in C_4F_8-only plasmas without bias [2,4,5]. Si_3N_4 surface shows slow initial nucleation, and F access is easy before continuity, and thickness increase is limited, and the layer on Si_3N_4 stays thin without bias [1,4]. H_2O addition increased the fluorocarbon layer thickness on Si_3N_4 and decreased it on SiO_2. The increase on Si_3N_4 is attributed primarily to hydrofluorination-driven NH_x/Si–F_x terminations that promote CF_x retention, and transient ammonium fluorosilicate(AFS) formation may also occur under HF/NH_x-rich conditions, although it was not directly detected in this study [7,8]. O_2 addition inhibits fluorocarbon growth by oxidizing carbon species and scavenging CF_x radicals [6]. These results demonstrate substrate-dependent control of fluorocarbon growth by gas-phase H_2O, and sidewall passivation can be tuned precisely, and selectivity and profile precision improve in advanced etching applications.

PS-ThP-39 Data-Driven Sputtering Yield Prediction for DC Magnetron Sputtering, ***Eunseo Lee****, Hae June Lee,* Pusan National University, Republic of Korea

Plasma-based sputtering systems are widely used for physical vapor deposition of thin films. Among them, DC magnetron sputtering offers enhanced ionization efficiency through the magnetic confinement of secondary electrons near the target, leading to high deposition rates. A key

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process parameter in this system is the sputtering yield, which represents the number of atoms ejected per incident ion. The sputtering yield is known to vary depending on the ion energy, angle, and target surface condition, particularly as the target undergoes erosion during prolonged operation. In this work, we present a machine learning based framework for predicting sputtering yield variation during target erosion in a DC magnetron sputtering environment. To generate data for model training, we performed a particle-in-cell with Monte Carlo collisions (PIC-MCC) simulation for argon discharge. From the simulations, we extracted time-resolved ion energy and angular distributions (IEADs), as well as spatially varying plasma parameters, such as potential and density, near the target surface. The extracted plasma features were used as input data for a supervised neural network (NN) model. The sputtering yield corresponding to each condition was calculated using Yamamura's semi-empirical equation based on the incident energy and angle of argon ions. The trained NN model is intended to capture complex nonlinear relationships between plasma dynamics and surface response to enable fast estimation of yield variations without relying on time-consuming physical simulations. This approach is expected to serve as a practical tool for analyzing the impact of target erosion and optimizing process control in magnetron sputtering systems.

PS-ThP-40 Ultra-Low Temperature Dopant Activation Enabled by Plasma Enhanced Annealing, ***Zhihao Ma,*** University of Texas at Dallas*; Mahsa Shekarnoush, Yuanning Chen, Malcolm Bevan, Harvey Stiegler,* MicroSol Technologies Inc.*; Lawrence Overzet,* University of Texas at Dallas

The formation of highly doped, ultra-shallow junctions is critical for the continued scaling of advanced semiconductor devices. However, achieving high dopant activation while preserving lattice integrity remains a fundamental challenge.

Conventional annealing techniques such as furnace annealing and rapid thermal annealing (RTA) typically require processing temperatures above 800 ℃ to activate dopants and repair implantation damage. Although effective, these high-temperature treatments inevitably induce excessive dopant diffusion, junction broadening, and thermal degradation of fragile device materials, restricting their suitability for next-generation technologies.

Plasma Enhanced Annealing (PEA) has emerged as a compelling alternative, offering an ultra-low thermal budget through localized and controllable energy delivery from plasma ions. By tailoring ion energy, flux, dose, and species, PEA enables efficient dopant activation at substantially lower substrate temperatures (300–500 ℃). This precise, near-surface energy transfer preserves shallow junction profiles, mitigates implantation-induced defects, and maintains device integrity while achieving high activation efficiency.

In this study, implanted silicon wafers were annealed using PEA, and their post-process properties were systematically evaluated using four-point probe measurements and Raman spectroscopy. Relative to conventional thermal annealing (TA) and RTA under identical conditions, PEA demonstrated noticeably superior electrical activation which is demonstrated by significantly reduced sheet resistance together with enhanced crystallinity. 500 ℃ PEA of shallow boron implants reached essentially the same sheet resistance as for RTA at 800 ℃. Moreover, a comparative analysis of different inert ion species revealed distinct influences on dopant activation efficiency and lattice recovery.

These results establish PEA as a robust and versatile technique for forming highly activated, thermally stable, ultra-shallow junctions, positioning it as a strong candidate for integration into next-generation semiconductor device manufacturing.

PS-ThP-41 Tailored Waveforms for Ion Energy Control in ALE Applications*,* *Sebastian Mohr, Hyungseon Song,* ***Lucy Manukyan,*** Quantemol Ltd., UK

Atomic layer etching (ALE) is increasingly used in the manufacturing of semiconductor tools as they give more control over the resulting etching profiles than traditional etching techniques. While different approaches to ALE exist, many of them employ plasmas in one or more steps of the ALE process, be it to use the neutral radicals produced in the plasma to alter the surface or the ions to remove the altered top layer [1].

For such applications, independent control of ion flux and ion energy is highly desirable. Single frequency capacitively coupled discharges (CCPs) do not offer this, as the input power affects both flux and energy. Dual frequency discharges allow this to some extent, but it is limited due to, for example, increased ionization by secondary electrons at high powers of the low frequency. Furthermore, traditional CCPs usually produce bimodal ion energy distribution functions which can cover several 10s to 100s of eV with sharp peaks at either end, so the ion energy cannot be easily limited to a small interval of energies, which is desirable especially for ALE applications, so that the ions remove the top layer of the surface but do not damage the underlying bulk [1].

An alternative approach to achieve this desired control are tailored waveforms. These can range from so-called asymmetric waveforms combining a fundamental frequency with even multiples [2] to non-sinusoidal waveforms typically consisting of sharp voltage peaks [1] followed by a relatively long interval of an almost constant voltage. While it has been demonstrated that these type of CCPs offer independent control of ion flux and energy and/or are able to limit the ion energy to narrow energy intervals, they have not yet been well studied in industrial applications.

This presentation will show continued efforts to simulate industrial applications of tailored waveform CCPs using the well-established 2D plasma simulation code HPEM [3]. In these discharges, the plasma is sustained via ICP coupling, while the tailored waveforms are applied to an rf-electrode staging the wafer. Former simulations have shown the intended effect in case of blank metal electrodes, i.e. almost monoenergetic IEDFs at the electrode. In the continued simulations, we investigate the effects of wafers on the produced IEDFs, for example via charging effects.

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Author Index

Bold page numbers indicate presenter