

Advances in EUV Lithography Room 316 - Session EUV-MoM

Advances in EUV Lithography II

Moderators: Alain Diebold, University at Albany-SUNY, Lior Huli, TEL, Gregory Denbeaux, University at Albany-SUNY, Kandabara Tapily, TEL

10:00am EUV-MoM-1 Pushing the Limits of High-Volume Manufacturing with EUV Lithography, Mike Lercel, ASML INVITED

EUV lithography has transitioned from an emerging technology to a core manufacturing enabler for advanced logic and memory. Continued innovation with EUV will sustain semiconductor scaling through the next decade. EUV is now established for critical layers in high-volume manufacturing, delivering a step-change in resolution relative to DUV and enabling continued transistor density scaling, while its evolution to higher numerical apertures (0.33 NA to 0.55 NA and beyond) will further improve resolution, simplify patterning, and reduce process complexity and cost through single-exposure solutions. Productivity, availability, and source power are continuing to evolve to make EUV cost effective while improvements in overlay and imaging continue EUV into future nodes. EUV is positioned within a holistic lithography strategy—integrating computational lithography, metrology, and systems—to control edge placement error and enable cost-effective scaling as device architectures evolve toward 3D integration. Overall, EUV for manufacturing will remain central to sustaining Moore's Law and enabling AI-driven semiconductor growth, with expanding opportunities across both 2D scaling and emerging 3D integration schemes.

10:30am EUV-MoM-3 High NA EUV Challenges and Opportunities, Christopher Penny, IBM Research INVITED

The recent demonstrations of High NA EUV lithography provide significant opportunities to extend scaling for future technology nodes. While many of the key capabilities of High NA EUV have been demonstrated, there remain many significant challenges that must be resolved for High NA EUV to be fully adopted in manufacturing. For example, initial demonstrations have demonstrated single expose patterning for interconnects at 21nm pitch and below; however, further co-optimization of the lithography and etch processes will be required to achieve yield and defectivity levels required for manufacturing. One specific challenge is the introduction of metal oxide resists, and the subsequent process optimization in resist, develop and etch that will be required. Minimizing defectivity (line breaks and bridges) and LER/LWR will continue to be challenging as pitches scale with High NA EUV. The introduction of new materials and processes, such as subtractive Ru patterning, may offer an alternate path to utilize High NA EUV for continued scaling.

11:00am EUV-MoM-5 Climate-Aware Semiconductor Manufacturing: the Pivotal Role of Lithography, Emily Gallagher, imec INVITED

The semiconductor industry is built on technological innovation, historically guided by familiar metrics: power, performance, area, and cost. Today, increasing emphasis on reducing electrical power demand and improving supply-chain resilience drives growing awareness of environmental impacts. Connecting manufacturing choices to climate impact can be challenging, particularly across highly complex process flows comprising more than 1,000 individual process steps. Addressing the processes that consume demands modelling. To this end, imec has developed a framework based on a bottom-up, virtual fab model to represent a high-volume manufacturing fab.

This "virtual fab" is used to identify global trends in semiconductor manufacturing and the dominant role that lithography plays. Through illustrative, lithography-focused examples, we demonstrate how design, process, and operational decisions influence impacts, and how quantified insights can guide lower-emissions manufacturing. Since performance optimization remains essential, we highlight the need to treat environmental impacts as co-optimized engineering objectives.

11:30am EUV-MoM-7 EUV Pattern Rectification by the Directed Self-Assembly (DSA) of Block Copolymers, Dustin Janes, Jon-L. Innocent-Dolor, Tokyo Electron America, Inc.

Leading edge manufacturing customers are installing 0.55 NA EUV tools into development fabs, but their resist selection is still uncertain. Interest exists in finding ways to extend chemically amplified resist (CAR) usage to tighter pitch while maintaining a robust etch budget for pattern transfer. EUV rectification by DSA is one strategy to achieve that goal while

increasing scanner throughput. Positive-tone developed CAR patterns were rectified by an integrated process flow containing intermediate etch and wet cleans process steps. The exemplary process benefit of DSA at 24 nm line-and-space pitch is achieving uLWR $3\sigma = 1.6$ nm and healing >99% of stochastic defects.

11:45am EUV-MoM-8 Real-Time Monitoring of Chemical Evolution in Vapor-Deposited Zn-Based Hybrid EUV Resists, Thi Thu Huong Chu, Dan N. Le, Minjong Lee, Dushyant M. Narayan, University of Texas at Dallas, USA; Nikhil Tiwale, Brookhaven National Laboratory; Oleg Kostko, Lawrence Berkeley National Laboratory; Chang-Yong Nam, Brookhaven National Laboratory; Jiyoung Kim, University of Texas at Dallas, USA

Extreme ultraviolet (EUV) lithography is a key enabling technology for sub-10 nm metal half-pitch semiconductor nodes.¹ However, establishing a clear relationship between EUV resist chemistry and lithographic performance remains critical for advancing next-generation patterning with enhanced sensitivity, resolution, and stochastic control.² The inherently transient and environment-sensitive nature of irradiation-induced chemistry in EUV resists, however, has limited direct experimental access to reaction pathways under realistic processing conditions.

To address this challenge, we report real-time monitoring of chemical evolution in vapor-deposited Zn-based hybrid EUV resists, providing operando insight into resist reaction mechanisms during e-beam/EUV exposure. In particular, we investigate the distinct roles of organic components (aromatic versus aliphatic) in molecular atomic layer-deposited (MALD) Zn-based hybrid resist thin films to elucidate their influence on sensitivity and patterning performance under both EUV and low-energy electron exposures. By combining operando techniques such as Fourier transform infrared (FTIR) spectroscopy and residual gas analysis (RGA), we directly track chemical bond transformations in real time, enabling the identification of key reaction steps associated with crosslinking and bond scission. Our results reveal distinct exposure mechanisms underlying the observed performance differences. Aromatic-based resists predominantly undergo deformation of aromatic rings, as indicated by a dip at the C=C bond in the FTIR spectrum during 80 eV electron exposure. In contrast, aliphatic systems form dense networks through coordination-driven bonding. Furthermore, we conducted complementary in-operando RGA and electron emission measurements under EUV flood exposure, which revealed the major by-products released during EUV exposure. Together, these findings provide a more comprehensive understanding of the chemical transformations that occur under realistic exposure conditions and highlight the value of real-time, operando approaches in linking molecular structure to lithographic behavior.

The insights provide guiding principles for designing next-generation vapor-deposited hybrid EUV resists with improved performance and reduced stochastic variability.

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[1] I. Giannopoulos *et al.*, *Nanoscale*, **2024**, 16, 15533–15543.

[2] T. Manouras *et al.*, *Nanomaterials*, **2020**, 10, 1593.

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1:30pm EUV-MoA-1 EUV Resists: Chemistry, Mechanisms and Challenges, Robert Brainard, University at Albany INVITED

The lithography community has studied EUV photoresists for nearly thirty years. Yet, some of the most basic details of the interaction of EUV photons with photoresists remain poorly understood. In a typical photochemical reaction using longer-wavelength light ($\lambda = 157\text{--}1000\text{ nm}$), photons create excited states in photoactive compounds, thereby creating known quantities of intermediates and photoproducts at measurable rates. The photochemical reactions occurring during EUV exposure are much more complex and, as yet, not fully explored.

This presentation will start with a quick introduction to photoresists and EUV lithography. It then will describe how 92 eV EUV photons ionize molecules in resists, creating holes and free electrons, and identify and discuss the individual interactions that occur with atoms (Figure 1). However, the number of electrons created, their reaction mechanisms, their lifetimes and their reaction cross-sections are not well known. The presentation will discuss experimental results and provide insight into these poorly understood aspects of EUV exposure mechanisms.

2:00pm EUV-MoA-3 The Effect of Molecular Weight and Polydispersity Index on the Ultimate Roughness of EUV Photoresists, Greg Denbeaux, University at Albany

In EUV lithography, one of the critical challenges is the line edge roughness (LER) or line width roughness (LWR) of the resist pattern. There are many contributing sources to the roughness in the resist including photon stochasticity. In this paper, we correlate molecular weight and the distribution of the molecular weight of the photoresist on the roughness of the exposed pattern using top-down low energy electron exposures and atomic force microscopy. Most of the results will be based on PMMA as a simple model system for exploration.

2:15pm EUV-MoA-4 X-ray Spectroscopy of EUV Exposed SnOx Nanocluster Thin Films Yields Insights Towards Radiolytic Mechanism, Trey Diulus, NIST-Gaithersburg; Priyanka Ketkar, NIST; Matthew A. Wade, NIST-Gaithersburg; Conan Weiland, Cherno Jaye, NIST; Daniel Sunday, R. Joseph Kline, NIST-Gaithersburg

The semiconductor industry is focused on optimizing extreme ultra-violet (EUV) lithography to fabricate leading edge microchips with smaller device features. Metal-oxide (MOx) nanoclusters are being developed as EUV photoresists due to high photon absorption cross sections at the EUV wavelength (13.5 nm) and smaller component size relative to chemically amplified photoresists. Thin films of organo-tin clusters can be made with precise control using solution-based methods, utilizing precursor fragments that link together to form a wide range of structures and compositions, but the radiolytic mechanism that induces a solubility change in these films is still elusive. To identify EUV induced chemistry, we have prepared organotin dodecamer resist films with varying EUV dose exposures and utilized a suite of several synchrotron-based x-ray spectroscopy measurements, specifically synchrotron source hard x-ray photoelectron spectroscopy (HAXPES) to interrogate changes in composition, x-ray absorption spectroscopy (XAS) to examine the electronic structure of the film components, resonant soft x-ray reflectivity (RSOXR) to identify changes in optical constants, and standard x-ray reflectivity (XRR) to track film density. With XAS, we are getting bond-specific information that complements the oxidation state information from the HAXPES. RSOXR provides nanoscale resolved optical constant depth profiles, which complement the surface sensitive XAS. HAXPES shows a decrease in C 1s intensity along with an increase in the O 1s corresponding to the metal oxide, a result expected due to removal of ligands and cross-linking that was previously mentioned. Comparing the Sn L-edge in the TEY XAS for the unexposed versus exposed regions display a clear increase in absorption intensity, as the cross-linked nanocluster forms more of a metal-oxo lattice. This increase in intensity suggests an increase in film density, which was explicitly seen in XRR as the unexposed density increases upon exposure. Further XAS images of the C and K-edges provide spatial information with a chemical contrast corresponding to the resonant absorption energy for the elements present in the film. Evidence of a carbonyl species formed upon EUV exposure can be seen, which may play a

role in the polymerization of the clusters. Overall, we highlight the importance of a comprehensive and multi-modal metrology approach that is necessary for providing improved resist designs for optimal performance. Identifying this chemistry will ideally lead to design of more efficient EUV photoresists that can help advance next generation EUV lithography.

2:30pm EUV-MoA-5 Closing the Stochastics Resolution Gap, Chris Mack, FRACTILIA INVITED

Background: Since the birth of the integrated circuit, electronics industry growth and innovation have relied on semiconductor manufacturers putting ever smaller features (described by their critical dimensions or CDs) into production. Yet today, stochastics, the randomness inherent to chip making near the atomic scale, is threatening the continued ability to manufacture the smallest possible features in volume production. **Aim:** To understand the impact of stochastics on semiconductor manufacturing today, the Stochastics Resolution Gap is defined and used as a framework assessing the value of reducing stochastics variability. **Approach:** This paper provides an introduction to stochastics, their emerging limitations on lithography resolution, technology solutions for improving resolution and yield, and the importance of accurate measurement technology for bridging the stochastics resolution gap. **Results:** Using one stochastics-aware design rule example, a method for determining the optimum via size in a specific 28-nm pitch process is presented in order to minimize the detrimental role of stochastics. **Conclusions:** The Stochastics Resolution Gap is a real limitation, but it is not fixed. Further efforts are needed to continue to close this gap.

3:00pm EUV-MoA-7 The Role of Environmental Humidity During Processing on the Properties of Indium Nitrate Sol-Gel EUV Resists, Cody Allen, Mohsen Moayedi, Raphael Nam, Kevin Brenner, Julia Hsu, The University of Texas at Dallas

As EUV lithography moves to higher numerical aperture patterning, appropriate photoresists must simultaneously meet increasingly stringent requirements for reduced resist thickness, high sensitivity, and low stochastic variability. Metal-containing resists offer improved EUV absorption compared with conventional light-element organic resists, with organotin (Sn-oxo) materials being a prominent example. Our group has investigated indium nitrate-based sol-gel photoresists as an alternative metal-oxide resist platform, as indium has an EUV absorption cross-section similar to that of tin. In this work, we examine how film formation and dose response of indium nitrate resist are influenced by ambient moisture during resist processing.¹

Because access to EUV exposure tools remains limited for academic research, we primarily evaluate resist contrast using 100-eV electron-beam exposure as a practical alternative. The energy of the electrons is similar to that of EUV photons, 92.5 eV. The indium nitrate resists demonstrate sensitivity comparable to that of the Sn-oxo resist and can be patterned by electron-beam lithography (EBL) into 50 nm half-pitch line/space features.^{2,3} EUV flood-gun dose curves further indicate sensitivities as low as $10\text{--}20\text{ mJ/cm}^2$.^{2,3} However, processing under elevated relative humidity produces nanoscale bump-like crystalline defects that degrade pattern fidelity by increasing line-edge roughness (LER).² Controlled-humidity processing suppresses these defects, enabling defect-free films made at relative humidities up to 35% RH.⁴ At 25% RH, defect-free line/space patterns were achieved with an LER of 2 nm and a linewidth of 19 nm.⁴

These preliminary results motivate a systematic controlled-humidity EBL study in which indium nitrate films will be processed across defined relative humidity conditions and evaluated by dose response, retained film thickness, linewidth, LER, and nanoscale defect density. Correlating these lithographic metrics with film morphology measured by atomic force microscopy and chemical characterization using Fourier transform infrared (FTIR) spectroscopy will clarify how water uptake alters hydrolysis/condensation chemistry, defect formation, and resist sensitivity. More broadly, this work can help identify the mechanism through which ambient moisture acts as a critical processing variable for solution-processed metal-oxide resists.

3:15pm EUV-MoA-8 Incorporating Bismuth into Hybrid Inorganic-Organic Films using Molecular Layer Deposition for Advanced Lithography Applications, Jane Keth, Duncan Reece, David Bergsman, University of Washington

To address the exponential rise in memory demand and improve energy efficiency per transistor, continued scaling of semiconductor feature sizes will be essential. The semiconductor industry has converged on the idea

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that achieving high-resolution patterning at sub-10 nm critical dimensions needed for next-generation devices will require extreme ultraviolet (EUV) lithography. Enabling this technology will further require photoresists compatible with EUV, often through incorporating high-Z elements that enhance radiation absorption. Several high-Z elements, such as tin, zirconium, hafnium, zinc, titanium, and indium have been investigated for use in metal-oxide or hybrid metal-organic photoresists for EUV/e-beam (EB) applications. However, many of the methods used to deposit these resists rely on wet chemical processing methods, such as spin-coating or sol-gel synthesis, which can complicate uniform ultrathin film formation and increase susceptibility to defects. One alternative approach for testing and manufacturing these resists is molecular layer deposition (MLD), which provides a compelling dry, solvent-free approach for photoresist fabrication. In MLD, vapor precursors are sequentially pulsed into a reactor, where they undergo self-limiting surface reactions to deposit molecular layers with precise thickness control. MLD is also amenable to area-selective patterning and high aspect ratio deposition, which could be used in processes inaccessible to chemical vapor deposition.

In this work, we examine a relatively underexplored hybrid MLD chemistry for use as a photoresist for EUV lithography: a Bismuth-based hybrid. Bi photoresists offer a promising photoresist candidate for EUV/EB lithography, due to its high EUV absorption and low toxicity comparatively to other high-Z metals. Here, we demonstrate the successful deposition of Bi-based hybrid MLD films. We describe the ambient and chemical stability of the biscone films, as verified by XPS and FTIR. We further expose the film to EB lithography to create a dose matrix and quantify the film's potential EUV-sensitivity. Through this work, we hope to expand the library of MLD chemistries and further demonstrate the potential for MLD as an approach for creating next-generation photoresist materials.

3:30pm EUV-MoA-9 High Purity Component Cleaning for EUV: Current Challenges in the Process Chain, *Michael Flaemmich*, VACOM USA

Unlike classic component cleaning, high purity cleaning for EUV Lithography is not about cleaning off large amounts of production residue (e.g. several gallons of oil per batch or several pounds of chips). Rather, high purity cleaning for EUVL focuses on removing even the slightest residual contamination (particulate, organic, and inorganic) and then keeping the cleaned surfaces clean and preserving them. As a consequence, the creation of high purity surfaces for EUVL is not only the task of the process step cleaning. This induces some familiar and some new challenges for cleaning technology and the entire process chain, which will be highlighted in the talk.

Furthermore, we will introduce our approach to transfer our high purity parts cleaning concepts for EUVL cleaning from Europe to the US. VACOM recently opened a parts cleaning facility in Lewistown, Montana. We will give some insights into the machines, processes and the current challenges in the high purity process chain for EUVL component cleaning.

Besides EUVL, industries requiring high-purity cleaning and ultra-clean parts are those where microscopic contamination causes component failure, product spoilage, or safety hazards, primarily semiconductor manufacturing, aerospace/defense, pharmaceuticals, and medical device production. These sectors necessitate specialized cleaning techniques to remove contaminants - such as particulate matter, lubricants, and ions - from surfaces, often requiring ISO-certified cleanroom environments.

4:00pm EUV-MoA-11 CD-RSoXS: Latent Image Metrology for Source-Mask-Resist Co-Optimization in High-NA EUV Lithography, *Cheng Wang*, Lawrence Berkeley National Laboratory

INVITED

As critical dimensions in extreme ultraviolet (EUV) lithography shrink below 10 nm, particularly for high-NA and hyper-NA systems with reduced depth of focus, three-dimensional effects and absorption gradients within photoresists become increasingly important. In this regime, latent image metrology is essential for co-optimization of the lithography stack, where the source and mask define the aerial image, and the heterogeneous photoresist chemistry governs subsequent reaction and development processes. We introduce critical-dimension resonant soft X-ray scattering (CD-RSoXS), a non-destructive metrology approach combining near-edge X-ray absorption spectroscopy, resonant scattering, and multiphysics modeling to probe 3D morphology and chemical profiles in photoresists. CD-RSoXS enables chemically sensitive characterization across lithographic stages, including latent image formation, post-exposure bake (PEB), and development, revealing nanoscale chemical gradients and structural evolution that drive stochastic variability. By directly mapping resist chemical heterogeneity and its evolution, CD-RSoXS provides critical input for co-optimization frameworks, linking aerial image design with material

response. Complementary RSoXR measurements further quantify underlayer properties and their influence on EUV absorption and resist performance. Machine-learning-assisted reconstruction accelerates interpretation of complex scattering data. Together, this work establishes CD-RSoXS as a powerful platform for latent image metrology and integrated materials-process co-optimization in next-generation EUV lithography.

4:30pm EUV-MoA-13 Outlook for Future EUV Patterning Opportunities and Challenges, *Eric Liu, Steven Grzeskowiak, Alexandra Krawicz, Katie Lukter-Lee, HungYu Chang, Surya Padinjarekutt, Yen-Tien Lu, Christopher Cole, Julian Michaels, Amrit Kaphe*, Tokyo Electron America, Inc.; *Akiteru Ko*, Tokyo Electron America, Inc., Japan

INVITED

EUV (extreme ultraviolet) lithography has been the major driving force behind extending device density scaling. In both logic and memory devices, EUV improves imaging resolution and enables single-print patterning to replace the complex multi-patterning method. This technology simplifies the process and reduces design complexity, promoting manufacturability and cost control for high-volume production. One of the fundamental challenges that we observed is the slowing down of pattern variation scaling. By leveraging advancements in lithography technology, such as the transition from Low NA (numerical aperture) to High NA EUV, and process integration solutions, such as self-aligned multiple patterning (SAMP), the minimum pattern scaling is theoretically achievable to meet the requirements of area scaling going forward. However, the pattern variation has not improved with the reduction of designed pattern feature, which has a significant impact on device reliability and a narrow process window across technology nodes.

Controlling pattern variation, reducing dose-to-size, and maintaining the imaging resolution are the classic patterning trade-off relationships. The challenges and opportunities are aimed for improvement in pattern variation and dose-to-size without the penalty in imaging resolution. In this presentation, we examine several technology options and innovations to realize the formation of minimum metal pitch at the advanced node. These technologies include:

1. Advancements in EUV lithography single patterning and self-aligned multi-patterning.
2. Patterning challenges and plasma interaction in MOR (metalorganic resist) system.
3. Innovative patterning and process integration solution to improve pattern variation.

5:00pm EUV-MoA-15 Edge Placement Error Reduction using Directional Etching for Via Resistance Improvement, *Jennifer Oakley, Takumi Nishinobo, Yen-Tien Lu, Jeffrey Smith, Reo Kosaka, Rintaro Yamamoto, Sheldon Meyers, Lior Huli, Eric Liu, Hirokazu Aizawa, Angeliue Raley, Luis Fernandez*, TEL US

Back End of Line (BEOL) metal pitches are projected to scale to ~18 nm by 2029–2030 and ~12 nm by 2035–2036 driving an increased need for precise Edge Placement Error (EPE) control. This work reports simulation and experimental demonstrations of post-lithography EPE correction using a Gas Cluster Beam (GCB) system. The GCB system performs nanometer-scale, location-specific film etching integrated with a wafer scanner. This system generates gas clusters from a fixed nozzle and uses scanner tilt and controlled wafer motion to deliver spatially selective etching in either X or Y directions. Chemistries were developed to enable etching of both organic and inorganic materials, permitting small, targeted adjustments to feature edges after lithography.

Simulations for a representative M0/M1 stack (16 nm M0 pitch, 28 nm M1 pitch, and 7 × 13 nm V0 slot via) indicate that correcting EPE by ~2 nm can reduce via resistance by over 20% for an M1 subtractive integration scheme, implying measurable device performance benefits. Experimentally, post-via-lithography GCB etching was applied to a two-level dual damascene Cu process (36p lower-level lines, 28–36p upper-level features) using a chemically reactive gas cluster to trim positive-tone chemically amplified resist. Controlled unidirectional etches showed predictable increases in via opening in the intended direction (CD growth consistent with programmed shifts) while preserving orthogonal CD. Measured overlay shifts matched expectations, demonstrating precise directional control.

To assess electrical impact, wafers were intentionally exposed with a 4 nm via misalignment; one set was corrected using GCB while a control set was left uncorrected. GCB-treated wafers reduced misalignment to under 1 nm and exhibited a ~17% decrease in via resistance at M2. TEM imaging confirmed restoration of via centering after GCB correction. These results

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validate GCB's capability to perform nanoscale, location-specific EPE corrections that improve critical BEOL electrical parameters. Future work will integrate measured overlay data into a Location Specific Processing (LSP) workflow to perform localized, data-driven corrections. The demonstrated GCB approach is extensible beyond BEOL to potential FEOL and other applications where sub-nanometer edge control can enhance device performance and yield.

5:15pm EUV-MoA-16 Measurement of H* Radicals and SnHx Vapor Species in a Simultaneous Deposition and Etch Experiment, *Jameson Crouse, Nathan Bartlett, Emily Greene*, University of Illinois at Urbana-Champaign; *Shiva Rajavalu, Sergio Ferraris, Niels Braaksma*, ASML; *Andrew Herschberg, David Ruzic*, University of Illinois at Urbana-Champaign

Extreme ultraviolet (EUV) lithography sources use Sn in the process of generating 13.5nm wavelength light. This Sn expands out and coats plasma facing devices around the source. H₂ buffer gas is added to mitigate transport to important surfaces such as the collector mirrors. Sn that has deposited on surfaces can only be removed in situ through etching by H*, which produces SnH_x in the gas phase. The EUV light generates a background hydrogen plasma, which includes varying densities of H* radicals. Knowledge of the local H* radical density is important for understanding the etch rate on wall segments throughout the device, and errors propagate, leading to incorrect predictions of Sn accumulation. This work seeks to validate diagnostics for radical measurement in EUV sources, along with validation of predicted etch rates through the lowering of error bars in a Sn etching experiment being conducted at UIUC. This presentation covers initial results from spatial OES measurement of hydrogen radicals in the presence of an ICP generated hydrogen plasma at pressures between 10-100mTorr, and powers between 1-200W. The presentation also will cover the development of a TALIF based H* radical diagnostic at UIUC for the measurement of H* radicals. The spatial OES data will be benchmarked using the TALIF system, with actinometry used to measure trends in H* radicals and approximate absolute radical densities. Development of a unique collisional radiative model for the H₂ plasma will be discussed with effects on local Sn gas species. Future work looking into Sn and SnH gas species will be addressed.

5:30pm EUV-MoA-17 Enabling an Accelerated Pathway Within the Us for Learning on Lowna Euv, Hina Euv and What'S Next, *Erin Lavigne*, NY CREATES

Within the Albany Nanotech Complex, a deeply integrated ecosystem of state-of-the-art semiconductor fabrication tools, advanced materials laboratories, and data-driven infrastructure is already accelerating breakthroughs across device, process, and systems research. The introduction of HiNA further amplifies this capability by providing a tightly coupled, pre-competitive environment optimized for high-velocity collaboration across academia, industry, and government. Researchers gain direct access to advanced lithography, deposition, etch, metrology, and integration platforms—co-located and orchestrated to support rapid learning cycles at leading-edge and beyond-CMOS nodes.

The impact is immediate and tangible: rapid screening, design-of-experiments, and prototyping workflows enable accelerated exploration of novel materials systems, heterogeneous integration strategies, and next-generation device architectures. From custom optical and electronic materials to advanced interconnect, memory, and logic concepts, iteration cycles are shortened through shared process modules, standardized interfaces, and real-time characterization. High-throughput experimentation, coupled with advanced modeling and data analytics, enables faster convergence on viable process windows while dramatically reducing cost and risk relative to traditional development paths.

By lowering barriers to access—whether capital, tooling, or organizational silos—HiNA enables ambitious, cross-disciplinary ideas to transition from theoretical concepts to validated hardware with unprecedented speed. The platform supports seamless scaling from early material feasibility through device demonstration and system-level integration, creating a continuous pipeline from discovery to manufacturable solutions.

This talk will examine the technical drivers and roadmaps underpinning this acceleration, including next-generation light sources for advanced patterning and metrology, emerging process integration schemes, and co-optimization strategies spanning materials, devices, and architecture. Equally important, it will detail the engagement and partnership models that make this ecosystem uniquely effective—highlighting how shared infrastructure, aligned incentives, and collaborative governance enable participants to innovate faster together than any organization could alone.

Plasma Science and Technology Room 315 - Session PS2+EUV-TuA

Plasma Processes for Feature Scaling

Moderators: Erwin Kessels, Eindhoven University of Technology, the Netherlands, Pingshan Luan, TEL Technology Center America

4:00pm PS2+EUV-TuA-8 Advanced Logic Pitch Scaling in the High NA EUV Era, Arame Thiam, Yannick Feurprier, TEL Europe, Belgium **INVITED**

High NA (0.55 NA) EUV lithography enables the single exposure of critical layers for future generations of logic (14A and below) and DRAM (1d and below) devices. Its implementation, however, introduces challenges in meeting both technology and high-volume manufacturing requirements. We will review and discuss the challenges of certain processes for logic use cases (Place and Route and Tip-to-Tip CD control, random logic via) and for the memory cases (contact holes and pillar). Co-optimization of the lithography process (resist, source, mask and development method) together with the etch pattern transfer process and the defectivity assessment enables the demonstration of a failure free process window for Place and Route (PnR) logic clips at tight pitches (down to 18 nm pitch) and for 28 nm pitch pillars for the memory use case.

The stringent tip-to-tip (T2T) CD control required by the technology in the PnR also creates opportunities for directional etch techniques. Gas Cluster Beam (GCB) technology can complement high NA EUV lithography by providing precise T2T CD control, reducing LER and helping to mitigate defectivity. Finally, further validation of the high NA EUV and etch patterning transfer is presented through electrical test.

Keywords: High NA EUV, Etch patterning, PnR, DRAM, Defectivity, Directional etch, Electrical test

4:30pm PS2+EUV-TuA-10 Dry Resist Patterning Solutions for High-NA EUV Lithography, Ali Haider, Lam Research Corp.; Zhengtao Chen, Shruti Jambaldinni, Lam Research Belgium BV, Belgium; Anuja De Silva, Lam Research; Rich Wise, Lam Research Corp. **INVITED**

High-NA EUV lithography patterning at increasingly tight pitches introduces significant challenges, including elevated defectivity, reduced depth of focus (DOF), shrinking process windows, and the need for dose reduction without degrading pattern quality. These challenges become increasingly severe near ultimate resolution at P18 L/S and limit the extendibility of conventional wet solution processed resists.

In this work, we demonstrate the performance of Lam's Aether® dry resist technology for dense P18 line/space patterning using high-NA EUV lithography. We address key challenges such as defectivity, DOF, and line wiggling through co-optimization of dry resist deposition, underlayer, post exposure bake (PEB), and dry development. We introduce next-generation dry resists based on novel precursor chemistries with enhanced EUV sensitivity, enabling reduced dose to size without compromising roughness, while expanding the defect-free process window through co-optimization with dry development. We further introduce new dry development schemes that increase the effective resist budget after development, resulting in improved defect performance and lower roughness.

To address the high NA EUV challenge of limited DOF and profile control, we have introduced 3D engineered dry resist films using multi layer deposition with controlled composition and tunable EUV sensitivity in the vertical direction.^{1,2} We show that 3D engineered resist provides lower dose to size, improved profile control, reduced line wiggling, and enhanced DOF.

Overall, we show that Aether dry resist and development solutions address key challenges in high-NA EUV P18 L/S through innovations in dry resist and development strategies with co optimization of process parameters.

¹Gulati, Saumya, et al. "Evaluating three dimensionally engineered dry resist film performance for 0.33 NA and High-NA EUV patterning." *Advances in Patterning Materials and Processes XLIII*. Vol. 13983. SPIE, 2026.

²A. Haider et al., "Advances of dry resist towards next-generation line-spaces patterning in high-NA EUV lithography," *Proc. SPIE 13686*, 1368608 (2025)

5:00pm PS2+EUV-TuA-12 Study of Electron-Induced Etching Mechanisms for Chromium and Ruthenium, Michael Hinshelwood, Gottlieb S. Oehrlin, University of Maryland, College Park; Hubertus Marbach, Michael Rimmel, Gerson Mette, Michael Budach, Daniel Rhinow, Klaus Edinger, Maik Szafarska, Carl Zeiss SMT GmbH, Germany

Chromium (Cr) and ruthenium (Ru) are materials critical for semiconductor manufacturing, particularly as part of DUV and EUV photomasks, respectively. Both can be effectively etched with plasmas containing both oxygen and a halogen. Cr can be etched through the formation of CrO_2Cl_2 or CrO_2F_2 , while Ru is etched through the formation of RuO_4 or volatile RuO_xCl_y . To limit surface damage caused by ion bombardment during plasma etching, there is significant interest in isolating ions from the reaction system.

Y. Li et al. demonstrated rapid etching of Ru by combining a low-energy electron beam (EB) with a remote plasma (RP)-created flux of O_2/Cl_2 -derived neutrals [1]. The combination of EB and RP resulted in a synergistic etch effect, while RP or EB alone caused either low-rate etching or growth. Here, we aim to describe the mechanism that leads to this synergistic effect and expand it to the etching of Cr, and also investigate how etching selectivity between the two materials may be achieved.

Using in-situ ellipsometry, we model the real-time etching and modification of the metal surfaces. This modelling is complemented by direct chemical characterization of the surface with X-ray photoelectron spectroscopy (XPS). In the case of Ru, we have found that the EB increases the uptake of Cl on the Ru surface, which in turn activates the Ru toward oxidation to volatile compounds. The growth rate and composition of this chlorinated layer formed by the EB are investigated via XPS measurements with increasing EB/Cl_2 exposure time. In the case of Cr, we find a stronger synergistic effect with F/O etch chemistry as opposed to Cl/O. The etch rate with RP alone is highly dependent on the oxygen percentage in the feed gas as well as the oxidation state of the Cr. With a fluorine-rich feed gas, the surface quickly forms a CrF_x passivation layer, preventing further etching. The EB can break through this passivation and continue the Cr etch process by forming vacancies that allow O radicals to diffuse into the surface and form volatile Cr-O-F compounds. By combining ellipsometric observations with chemical quantification from XPS, we obtained mechanistic insight for the development of low-damage etch processes for Cr and Ru, and insights on paths to high Cr hard mask and Ru capping layer selectivity.

[1] Y. Li et al., "Investigation of ruthenium etching induced by electron beam irradiation and O_2/Cl_2 remote plasma-based neutral fluxes: Mechanistic insights and etching model," *J. Vac. Sci. Technol. A*, vol. 43, no. 2, p. 023005, Feb. 2025, doi: 10.1116/6.0004219.

5:15pm PS2+EUV-TuA-13 3 Layers Dielectric Patterning in Grid Module for OSC 3DDRAM Application, Yuchao Jiang, Jeongsoo Kim, Alejandro Fernandez Rodriguez, Hemant Kumar Raut, Nouredine Rassoul, Eren Canga, Robert Carpenter, Attilio Belmonte, Katia Devriendt, IMEC, Belgium

3 layers dielectric patterning in Grid module for OSC 3DDRAM application

Yuchao. Jiang¹, Jeongsoo Kim¹, Alejandro Fernandez Rodriguez¹, Hemant Kumar Raut¹, Nouredine Rassoul¹, Eren Canga¹, Robert Carpenter¹, Attilio Belmonte¹ and Katia Devriendt¹

¹Imec, Kapeldreef 75, B-3001 Heverlee, Belgium

DRAM applications have reached a limiting point with 2D design (planar device) because of the process challenges for ~12nm nodes and scaling difficulty of density. Since 2011, monolithic 3DDRAM has been explored with different integration approaches (HBL, VBL, capacitorless etc), and recently it has experienced renewed interest by major players in memory market.

In this presentation, a dry-etch process for grid patterning in MOLD-based monolithic 3D DRAM was reported, the process enables robust isolation of active regions in vertical-bit-line architectures. The method addresses morphology degradation and sidewall profile asymmetry arising from pattern-loading effects and hard-mask facet evolution in multi-layer SiN/SiO_2 ONO stacks. By optimizing passivation balance, ion directionality, and process conditions, the approach achieves stable dielectric grid formation with controlled critical dimensions and near-vertical sidewalls. The demonstrated process provides reproducible grid patterning suitable for high-aspect-ratio 3D DRAM integration. In monolithic 3DDRAM with MOLD-based vertical-bit-line (VBL) architecture, the Grid module (SINGRID) is the key dielectric-etch step that isolates active areas by etching through a multi-layer SiN/SiO_2 ONO structure (~355 nm). The grid lines have tight CD requirements and require near-vertical profiles (>87°) to ensure VBL alignment and prevent capacitor/gate shorts.

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The grid exhibits major-axis vs. minor-axis HM (hard-mask) facet differences, caused by imbalanced ion/radical flux between dense vs. semi-dense regions. Consequences include:

1. Unequal CD narrowing
1. Facet tilt differences (leading to asymmetric top rounding)
2. Risk of local bowing when ARDE.

For morphology improvements, a leaner DARC open step is applied (with reduced CHF3 and increased CF4/O2 flow) to reduce the morphological deformation.

For sidewall profile improvements, the process mitigates these effects through controlled anisotropic dry etching, combining directional ion bombardment with carefully tuned sidewall passivation.

5:30pm PS2+EUUV-TuA-14 Role of Interfacial Force Balance in Gap Filling of TEOS-based Flowable CVD: Insights from Molecular Dynamics, Hu Li, Tokyo Electron America Inc.,; Takeo Nakano, Nobuo Matsuki, Masaaki Matsukuma, Tokyo Electron Ltd., Japan; Raymond Joe, Anthony Dip, Tokyo Electron America Inc.,

Achieving void-free gap filling in high-aspect-ratio structures is one of the key challenges in advanced semiconductor processing. Flowable chemical vapor deposition (CVD) has been widely studied as a promising approach, and its behavior is often interpreted in terms of wettability or viscosity. However, these conventional descriptors do not always explain the differences observed in gap-fill performance across various precursor chemistries and geometries.

In this work, we focus on the pre-cure stage of flowable CVD and investigate the transport-driven filling behavior using classical molecular dynamics simulations. By intentionally excluding chemical reactions, we isolate the role of intermolecular interactions and interfacial forces in confined geometries. The simulation system consists of siloxane-based liquids on SiO₂ substrates, with trench structures of varying aspect ratios.

To better understand the filling mechanism, we introduce a force-based analysis by decomposing the total force acting on liquid molecules into liquid-substrate and liquid-liquid contributions. This approach reveals a clear spatial variation in the driving forces within the trench. Near the sidewall, strong downward forces promote infiltration, while in the center region, the driving force is significantly reduced, which leads to incomplete filling and void formation.

We further show that increasing the aspect ratio enhances this imbalance in force distribution, making uniform filling more difficult. In addition, surface modification, such as Si-rich surface, can reduce the interfacial interaction strength and improve liquid mobility.

These results suggest that gap-fill behavior cannot be fully described by wettability alone, and that a force-based perspective provides more direct insight into the underlying mechanism. This study offers a more detailed understanding of pre-cure transport processes and may help guide the design of future flowable CVD processes.

Advances in EUV Lithography Room Ballroom A - Session EUV-ThP

Advances in EUV Lithography Poster Session

EUV-ThP-2 Understanding the Initial Deposition and Etching of Tin in an Extreme Ultraviolet (EUV) Source, Nathan Bartlett, Jameson Crouse, Andrew Herschberg, Emily Greene, Jaime Robertson, Lucia Suarez Heredero, Marisol Velapinato, Karl Vu, University of Illinois at Urbana-Champaign; Niels Braaksma, Sergio Ferraris, ASML; 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. The interaction of hydrogen plasma species and tin lead to complex morphologies. In this work, we study the initial growth of tin thin films in a relevant hydrogen plasma environment. Tin is deposited using a high temperature thermal evaporation source and a hydrogen plasma is generated using an RF power supply. Thin films are measured using a scanning electron microscope and resistivity probes. The plasma is measured using optical emission spectroscopy, Langmuir probes, and radical probes. Impurity gasses, such as water, are also injected into the experiment to determine the effect on tin growth and etching. Water is expected to affect surface reactions which in turn increases the concentration of hydrogen radicals in the plasma. These results are used to validate both plasma models as well as tin thin film growth models.

EUV-ThP-3 Development of Mass Limited Targets for Enabling Fundamental Studies of Next Generation of EUV Lithography, Ajay Karakoti, Peipei Wang, Mathew Polek, Tyler Ray, Sivanandan Harilal, Pacific Northwest National Laboratory

Extreme ultraviolet (EUV) lithography at 13.5 nm is a cornerstone of advanced semiconductor manufacturing, where continued device scaling depends on improvements in source brightness, spectral purity, and optics lifetime. The ANGEL (Accelerating Next-Generation EUV Lithography) project, led by Pacific Northwest National Laboratory, targets significant improvements in the conversion efficiency of EUV sources based on low-density Sn targets by carrying out fundamental experimental studies and modeling to understand and control the underlying plasma physics.

Studies of laser produced plasma from bulk Sn sources emit substantial particulate, ionic, and neutral debris, with high-velocity ions and neutrals capable of damaging nearby collection optics. In addition, fully dense Sn plasmas produce a broad recombination continuum that limits spectral purity in the in-band region around 13.5 nm. Mass-limited, low-density targets, in which Sn is dispersed as a dilute dopant within a low-Z foam matrix, offer a route to mitigate both issues. Incorporating Sn as an impurity in a low-Z host reduces the average plasma ionization state and recombination continuum, narrowing the unresolved transition array (UTA) around 13.5 nm, while simultaneously limiting the total Sn inventory available to generate debris. Low-density foam targets further provide a well-defined geometry and density prior to laser illumination, enabling reproducible laser-plasma interactions.

This poster presents the fabrication and comparative characterization of Sn-doped mass-limited foam targets synthesized from two distinct low-Z matrices. It compares the performance of resorcinol-formaldehyde (RF) aerogels, a well-established foam chemistry for laser-plasma targets, and nanocrystalline cellulose (NCC) foams, an emerging bio-derived alternative. We compare the (i) ease and reproducibility of synthesis, (ii) morphology, Surface area and pore-size distribution, and (iii) spatial uniformity of Sn dispersion as characterized by different in-situ and ex-situ tools. Finally, we correlate these structural and compositional metrics with EUV emission characteristics, comparing the spectral profiles of doped RF and NCC foam targets against bulk Sn references to assess their suitability as mass-limited targets for spectrally clean, low-debris EUV generation.

EUV-ThP-6 Investigation of Cold Spitted Sn Particle Transport in a Hydrogen Plasma, Jaime Robertson, University of Illinois at Urbana-Champaign

In Extreme Ultraviolet (EUV) lithography, defectivity in printed wafers is a significant concern due to yield loss. Defects hinder the performance of

semiconductors, dependent on its size and location. Defectivity, in relation to this work, arises from the migration of particles and the subsequent contamination that occurs when these particles stick to sensitive components. This includes the reticle, which holds the pattern to be printed on the wafer. Sn particles are a significant contributor to reticle defectivity, resulting in substantial downtime for EUV machines at customer fabs. Sn defectivity arises from the complex interaction mechanisms of Sn particles with EUV-induced plasma. Each of these pathways contributes to the overall presence and movement of Sn particles within the system, potentially leading to contamination of sensitive components. These mechanisms need to be investigated in detail to tackle Sn defectivity and ensure high uptime for EUV machines, as understanding each process can inform the development of targeted mitigation strategies. Therefore, the studies described here investigate the interactions between hydrogen plasma, similar to the EUV scanner environment, and Sn found in certain regions within the EUV scanner. Three known plasma material interactions occur with Sn, which result in mass migration. These include ion etching, chemical etching, and electrostatic particle lift-off. Although these methods have been studied to varying degrees, modeling of the EUV scanner has shown that these mass migration processes cannot contribute to particles reaching the reticle. Therefore, the aim has been to determine whether other methods of mass migration occur, which result in particles found on the reticle. Specifically, cold spitting has been proposed as a potential mechanism for particle migration to the reticle. Cold spitting refers to the ejection of solid particles due to a buildup of hydrogen gas beneath the surface. Once the pressure of hydrogen bubbles formed is sufficiently high, the bubble bursts, ejecting nano-particles away from the surface. The difficulty in independently studying cold spitting has been in separating the migration mechanisms to ensure that the particles analyzed were formed by cold spitting. We present a method which allows for cold spit Sn particles to be collected on an adjacent surface while preventing particles formed through other mechanisms from being captured. Therefore, proving that cold spitting occurs for Sn. From the initial findings, the rate of ejections from a 1cm² sheet of Sn was approximated. The resulting flux was $5.1 \times 10^{11} \pm 15n \text{ particles/cm}^2\text{s}$.

EUV-ThP-7 Open-Use, Synchrotron-Based EUV Exposure/Characterization System at LLS, Ali Parastesh, Anthony Engler, Phillip Sprunger, Louisiana State University

A designated synchrotron-based EUV exposure/characterization system has been commissioned at the Louisiana Light Source, or LLS (LSU's Center for Advanced Microstructures and Devices). Using both a toroidal mirror and a Si/Mo multilayer spherical mirror, the system delivers focused EUV light (~2% bandpass centered at the required 13.5 nm wavelength) to the sample holder, with a simulated FWHM spot size of $\sim 1.2 \times 0.5 \text{ mm}$ at $\sim 3 \text{ W/cm}^2$. In addition to a low-energy external electron gun, an in situ quadrupole mass spectrometer and a hemispherical electron analyzer (with an X-ray source) enable operando characterization of photoresists during EUV exposure. The goal is to elucidate key aspects of the physics and chemistry of EUV exposure mechanisms and to better develop photoresists with enhanced performance (higher sensitivity, lower line edge roughness, and higher resolution) than those currently used in high-volume chip manufacturing. The beamline is an open-use EUV exposure/characterization facility for both academic and industrial users.

Initial studies on polyaldehyde-based resists capable of thermally driven, dry development are underway. Specifically, we have studied the effects on thin-film poly(phenyl glyoxal)s (PPG). Employing 100eV electrons, soft-X-ray XANES of the O- and C-edges reveals details of carbonyl elimination and the conversion of the pristine PPG backbone to a degraded state capable of developing the latent image. These results are supported by EPR, consistent with a Norrish mechanism of photodegradation.

EUV-ThP-8 Development and Performance of a University-Scale EUV Lithography Source, Dren Qerimi, University of Illinois; Sebastian Rojas Barragan, University of Illinois at Urbana-Champaign

To expand our lab's capabilities in EUV photoresist research, we developed an in-house EUV light source that provides lithography exposures at a cost feasible for a university setting. The system uses an Nd:YAG laser to produce plasma on a tin target, which generates EUV radiation without relying on the extremely expensive infrastructure found in commercial systems. A 150 nm zirconium transmission filter isolates the EUV wavelengths and allows direct exposure of the photoresist. The exposure dose is monitored in real time using an EUV-sensitive photodiode, and we have confirmed the accuracy of these measurements through successful exposures and development of EUV photoresists. Using this setup, we have

demonstrated a clear contrast curve with exposure times typically under 120 seconds, showing that the system can reliably deliver controlled and repeatable EUV doses. During optimization, we adjusted the laser power, the focusing conditions, the chamber pressure, and the movement of the target to stabilize the dose and improve EUV output. Debris from the plasma remains one of the primary challenges, so we are continuing to refine the target handling and filtering approach to extend the lifetime of internal components. Even with ongoing improvements, the system already provides consistent and tunable EUV exposure that supports photoresist testing and development. Compared to commercial EUV lithography platforms that cost several million dollars, this tool offers a practical and flexible option for research. It enables the study of new photoresist materials, dose response behavior, and exposure strategies without depending on limited industrial access. Current work includes blanket exposure testing and efforts to lower the required dose for full development. In this way, the system provides a meaningful bridge that allows academic research groups to work directly in the EUV regime.

EUV-ThP-9 A Computational Molecular Framework to Investigate EUV Lithography Photoresist Sensitivity: Poly(Phthalaldehyde) and Poly(Methyl Methacrylate) Degradation Study, Amrutha Raghu, Louisiana State University; **Tianyi Wang,** Louisiana State University; **Revati Kumar,** Louisiana State University

High-volume EUV lithography at sub-7 nm nodes is constrained less by optics than by photoresist performance. The resolution-LER-sensitivity tradeoff tightens with every technology node, and stochastic failures from photon shot noise set hard limits on what current resist platforms can deliver. Chemically amplified resists compound the problem by introducing chemical inhomogeneity that worsens stochastic acid generation and diffusion at the length scales that matter for sub-10 nm features. Single-component depolymerizable resists such as poly(phthalaldehyde) (PPA) avoid acid diffusion entirely, and cyclic PPA (c-PPA) achieves spontaneous dry development at doses competitive with CARs. Two questions have remained open: why does cyclic topology outperform linear PPA in EUV sensitivity, and what drives dose-dependent crosslinking at higher doses? We address both using reactive molecular dynamics with the ReaxFF force field. The framework simulates the aftermath of EUV-induced ionization through the Primary Knock-on Atom (PKA) method: backbone carbon atoms are randomly selected across a 40-chain, 20-mer simulation box and assigned velocities equivalent to 10 eV secondary electron momentum, then the system evolves chemically in an NVE ensemble. The same protocol is applied to PMMA, a well-established EUV photoresist with extensively characterized experimental behavior, making it an ideal validation system. Together, PPA and PMMA allow us to connect repeat unit structure and polymer topology to the full spectrum of EUV-induced chemistry and establish molecular design principles for next-generation photoresist platforms. PKA recoil redistributes charge across the simulation system, generating active sites whose charges deviate significantly from equilibrium. For PPA, c-PPA shows 3.6 times more active sites than l-PPA, and active site locations correlate directly with bond breaks, indicating elevated bond stress from energetic neighboring atoms. The origin is thermodynamic: the ring blocks angular relaxation that linear chains use to absorb the perturbation, forcing energy into bonds instead. Bond angle distributions, angle strain, conformational entropy, and radius of gyration all support this picture. For PMMA, PKA simulations show backbone bonds undergo higher scission than side-chain linkages, consistent with experimental EUV chemistry of methyl methacrylate polymers. This is traceable to the higher concentration of active sites on the backbone relative to side-chain carbons. Active site distribution and bond stress together explain the emergent EUV chemistry in both systems and provide a structural basis for rational photoresist design.

EUV-ThP-10 Accelerated Evaluation of Blister Formation in EUV Photomasks through Control of Hydrogen Ion and Radical Flux, Takayoshi Tsutsumi, Nagoya University, Japan; **Wataru Nishida, Yukihiro Matsumoto,** AGC Inc., Japan; **Kenji Ishikawa, Masaru Hori,** Nagoya University, Japan

Hydrogen plasma induced by EUV irradiation is generated from the hydrogen gas introduced into EUV scanners to suppress hydrocarbon contamination. Reactive hydrogen species, such as ions and radicals in the plasma, promote the formation of interfacial voids, which can subsequently grow into blisters in EUV masks. Although blister formation mechanisms have previously been studied through exposure to hydrogen radicals alone or through simultaneous exposure to ions and radicals, quantitative measurement and independent control of their fluxes and energies have been insufficient. As a result, the irradiation conditions, including the energy of reactive species and their respective doses, often differ

significantly from the actual exposure environment in EUV scanners. Furthermore, although multiple mechanisms for blister formation have been proposed, differences in the interfacial voids generation mechanisms arising from variations in species energy and their respective doses make it difficult to elucidate the blister formation mechanism under realistic EUV scanner conditions using conventional experimental approaches.

To address the issue, we developed an experimental methodology based on two key components: (1) control of gas-phase reactive species using a plasma reactor that enables independent control based on quantitative measurements of radical fluxes, ion fluxes, and ion energies, and (2) real-time monitoring of surface reactions through *in-situ* surface analysis techniques. Ion fluxes and energy distribution functions were measured using a Retarding Field Energy Analyzer (RFEA), whereas the absolute density of ground-state atomic hydrogen radicals was determined by vacuum ultraviolet absorption spectroscopy (VUVAS).

By quantitatively measuring and independently controlling reactive species, we demonstrated that the ion and radical flux plays a critical role in determining the onset of blister formation, as well as the morphology and density of the resulting blisters.

Thin Films

Room 321 - Session TF+AP+EUV-FrM

Atomic Scale Patterning and Processing

Moderator: Mark Losego, Georgia Institute of Technology

8:15am TF+AP+EUV-FrM-1 Expanding the Library of Mask Materials for Selective Area Growth by Molecular Beam Epitaxy, Corey White, Subhashree Seth, Daniela Montes, Daniel Bernstein, Tufts University; **Cornell Horne Jr.,** University of Illinois Urbana-Champaign; **Minjoo Larry Lee,** University of Illinois at Urbana Champaign

Selective area growth (SAG) enables laterally structured semiconductor growth as well as seamless encapsulation of foreign mask materials and, thus, presents an appealing approach to the monolithic integration of dissimilar materials. During SAG, III-V growth is carried out at relatively high substrate temperatures and slow growth rates to mitigate the formation of deleterious polycrystalline material on the patterned mask.¹ Historically, SiO₂ and Si₃N₄ have reigned as the most prevalent mask materials for SAG by molecular beam epitaxy (MBE).² However, successfully utilizing new mask materials with unique properties could unlock new applications and functionalities for hybrid structures. Here, we first elucidate the properties of mask materials that determine their suitability for SAG. By comparing SiO₂ masks synthesized by different thin film deposition methods, we find that differences in SiO₂ surface roughness, stoichiometry/density, and hydrocarbon contamination all impact the adsorption of group-III adatoms during epitaxial growth. Demystifying the relationship between mask material properties and the propensity of group-III adatoms to nucleate on the mask during epitaxy not only lays the foundation to achieve SAG under less stringent growth conditions over optimized masks and predict the effects of tool-to-tool variation, but also enables the identification of new, untested mask materials that may also be suitable for SAG. Thus, in this work, we showcase complete selectivity for GaAs growth over ZrO₂ and HfO₂ masks for the first time.³ This is achieved at approximately half of the group-III flux that can be employed for growth over SiO₂ with near-perfect selectivity due to differences in adatom desorption probabilities. Faceting of GaAs grown selectively within ZrO₂ gratings is found to be consistent with nominally identical growth within SiO₂ gratings. Namely, the facets that emerge depend wholly on crystallographic orientation of the dielectric mask patterns with growth within [010]-aligned structures being especially well-suited for epitaxial lateral overgrowth. III-V SAG over ZrO₂ and HfO₂ has applications in on-chip integration of passive and active optical components and deterministic growth of three-dimensional ferroelectric devices, but also demonstrates the exciting potential of further expanding the palette of available mask materials. Further work integrating other novel dielectric and two-dimensional mask materials will be presented at the conference.⁴ F. E. Allegretti and T. Nishinaga, *J. Cryst. Growth* (1995).² D. J. Ironside et al., *Prog. Quant. Electron.* (2021).³ R. C. White and M. L. Lee, *J. Vac. Sci. Technol. A* (2026).

8:30am TF+AP+EUV-FrM-2 Hybrid Molecular Layer Deposition of Tin-Aminates Toward EUV Resists, Alex Persson, Long Than, Stacey Bent, Stanford University

The leading edge of today's semiconductor manufacturing technology relies on extreme ultraviolet (EUV) lithography, utilizing a short 13.5 nm wavelength – a roughly fourteenfold reduction from the 193 nm ArF sources of previous deep ultraviolet (DUV) lithographic technologies. Use of this wavelength has dramatically reduced achievable critical dimensions, with new high-NA EUV tools resolving half-pitches as fine as 8 nm. However, the development of photoresists capable of translating this resolution into reliably patterned features has not kept pace with the breakthroughs in EUV exposure tools, making this material challenge a bottleneck to continued semiconductor scaling.

Conventional organic resists absorb EUV photons inefficiently, compounding stochastic failures at the ultrathin film thicknesses that pitch scaling now demands. The present work incorporates tin in an organometallic resist to address the need for better absorption, while amine organic linkers enable a tunable solubility switch using a metal-amine bonding motif not yet reported in such resists. Hybrid molecular layer deposition (MLD) is used to deposit this Sn-amine material one molecular layer at a time through alternating, self-limiting surface reactions between chemical precursors. This vapor-phase deposition technique affords molecular-level control over film thickness and structure, providing

smooth and conformal ultrathin films while avoiding the challenges of solvent processing.

This presentation will introduce hybrid MLD procedures for depositing Sn-aminates as a new set of materials using tetrakis(dimethylamino)tin as a tin precursor with ethylenediamine and p-phenylenediamine as amine linkers. The stability of these materials in air and in various developers is reported, providing insight into their solubility switch mechanism and lithographic process optimization. Electron-beam lithography (EBL) is employed as an EUV proxy, and initial results indicate that Sn-aminates act as promising positive-tone e-beam resists in various developers, including HCl, KOH, and TMAH. The effect of deposition temperature on film structure, composition, stability and EBL patterning quality is discussed between 70 °C and 150 °C. Lower temperatures led to higher growth rates and higher organic content in the films, and accelerated film oxidation and decomposition in air. Optimal patterning was found with films deposited at 90 °C using ethylenediamine as the organic linker and developed in 0.02 M KOH, resulting in a dose-to-clear of 12 mC/cm² with a full-pitch of 25 nm. The effect of air-aging and post-exposure baking is also discussed.

8:45am TF+AP+EUV-FrM-3 A Multivariate Approach Based on Residual Gas Analysis for Understanding Model Photoresist Processes Occurring During Exposure, Muhammad Ramzan, University of Mississippi, Pakistan; **Markus Langner,** University of Mississippi, Germany; **Kas Andrie, Meng Zhang, Bernhard Lüttgenau,** Lawrence Berkeley National Laboratory (LBNL); **Won-Il Lee, Md Istiaque Chowdhury, Xinpei Wu,** Brookhaven National Laboratory; **Melinda Lin,** Stony Brook University; **Nikhil Tiwale, Qin Wu, Qi Zhang, Cheng Wang, Ricardo Ruiz, Michael D. Connolly, Oleg Kostko,** Lawrence Berkeley National Laboratory (LBNL); **Chang-Yong Nam,** Stony Brook University/Brookhaven National Laboratory; **Michael J. Eller,** University of Mississippi

Photoresist processes such as photon absorption, electron generation, bond cleavage, crosslinking, and volatile-product formation are key challenges in extreme ultraviolet lithography (EUVL) that need to be understood and resolved. Here, we investigate functional-group-dependent EUV exposure chemistry using simultaneous total electron yield (TEY) and residual gas analysis (RGA) measurements on a library of model polymer photoresists with defined repeat-unit structures, including methacrylate, acid-functional methacrylate, hydroxyl-containing methacrylate, ether, aromatic, heteroaromatic, imide-containing, chemically amplified epoxy, and metal-oxide-infiltrated polymer systems. Principal component analysis (PCA) was applied to the mass spectrometry data from the RGA as an unsupervised dimensionality reduction technique. Firstly, PCA clearly differentiated between low- and high-outgassing photoresists, with high-outgassing photoresists driving the maximum variance in PC1 (24.5 %). Characteristic signals from the PC loading plots were identified and assigned to corresponding photoresists. Two fragment ions, m/z 31 (CH₃O⁺) and m/z 45 (C₂H₅O⁺), were observed during the exposure of polyethylene glycol (PEG) and poly(2-hydroxyethyl methacrylate) (PHEMA). Despite having identical mass-to-charge ratios, they exhibited opposite trends with respect to exposure dose. PEG displayed increasing intensity, whereas PHEMA showed a decrease with increasing exposure dose. This trend was attributed to differences in the scission mechanisms, with PEG undergoing a solubility switch via main-chain scission, while PHEMA undergoes side-chain scission. This allows us to distinguish these two mechanisms by the time-dependent response of characteristic fragment species. We also examined the relationship between TEY and various outgassing species and found that m/z 44, assigned to CO₂, showed a positive correlation (R²=0.99) with TEY in metal-oxide-infiltrated polymer systems, whereas no correlation was observed in PMMA-only resists. Showing that these infiltrated resists exhibit improved electron production and increased outgassing, both of which are critical to improving resist sensitivity. Moving forward, we anticipate our approach will be extremely useful for screening unknown resists and identifying their mechanisms.

9:00am TF+AP+EUV-FrM-4 A Single Amine Additive as Both Catalyst and Inhibitor for Area-Selective SiO₂ ALD, Jeong-Min Lee, Stacey Bent, Stanford University

Driven by the demand for atomic-scale precision patterning in advanced semiconductor processing, area-selective atomic layer deposition (AS-ALD) has emerged as a paradigm-shifting technique in nanofabrication, leveraging its bottom-up nature to enable spatially selective and precise film growth. In this work, we report a methodology for achieving accelerated deposition of SiO₂ thin films on SiO₂ surfaces while suppressing growth on metal oxide surfaces using a single additive molecule that acts as both catalyst and inhibitor. To overcome the limited selectivity of

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conventional SiO₂ AS-ALD processes associated with the use of strong oxidizing agents, we introduce a catalytic SiO₂ ALD process. This process employs a Lewis-base catalyst that both promotes SiO₂ growth with H₂O as a mild reactant at temperatures as low as 100°C, and simultaneously inhibits growth on metal oxide surfaces such as Al₂O₃, TiO₂, RuO_x, and CuO_x. Results show that the catalyzed ALD process using amine additives exhibits a mild inherent growth suppression on metal oxide surfaces—but not on SiO₂—suggesting that interactions between the Lewis-base catalyst and metal oxide surfaces during co-injection with the precursor contribute to the retardation of SiO₂ growth. To further enhance the selectivity between SiO₂ and metal oxide substrates, an amine pretreatment was performed prior to ALD to amplify the blocking capability of the same amines as inhibitors. Comparative evaluation of pyridine and triethylamine revealed different inhibition behaviors depending on the underlying metal oxide surface, with triethylamine providing more effective growth inhibition on Al₂O₃ and TiO₂ surfaces than did pyridine. By combining the inherent growth suppression of the catalyzed ALD process with the additional blocking effect of amine pretreatment, enhanced selectivity for SiO₂ deposition on an SiO₂ growth surface and several metal oxide nongrowth surfaces was achieved. This work provides a new strategy for broadening the applicability of SiO₂ AS-ALD by leveraging the dual functionality of amine additives for both catalytic growth and surface inhibition.

9:15am TF+AP+EUV-FrM-5 Ultrasonic Level Sensing for ALD Precursors Through the Ampoule Wall, *Paul Dreher*, Inficon, Liechtenstein

Precursor inventory is one of the least directly observed state variables in an ALD delivery system. It is normally inferred from run time, wafer count or recipe demand rather than measured, so the estimate drifts over the life of the source and anomalous draw down remains invisible. Where sensing is fitted it usually detects liquid presence at a few fixed heights using an element immersed in the precursor, which quantises the reading and adds a wetted surface to a corrosive high purity path.

We determine remaining liquid height from outside a stainless steel ampoule by ultrasonic pulse echo. A piezoelectric element coupled to the outer face of the vessel base launches a longitudinal pulse through the wall. The acoustic impedance contrast between steel and a typical precursor is large, so most energy is reflected at the wall, but the transmitted fraction is sufficient to produce a resolvable echo from the liquid vapor interface. The vessel wall itself becomes part of the acoustic path and no feedthrough or wetted surface is introduced.

Extracting height is an underdetermined inverse problem. The echo delay gives the product of propagation velocity and path length, while the quantity of interest is the path length alone. Sound velocity in these liquids is strongly temperature dependent with a coefficient specific to each chemistry, and ampoules operate at temperatures up to 200 °C, so a calibration taken at room temperature does not transfer. The chemistry itself may also be unknown to the operator. We show that the velocity can be recovered in situ at operating temperature from the same acquisition, so height is determined with no prior property data for the fluid.

Silicone oil was used as a deliberately unfavorable test case: attenuation is high, the surface echo is correspondingly weak and higher order reverberations within the liquid produce competing arrivals that must be separated. Recovered height agrees with an independent reference to approximately 1 mm with R² = 0.997, continuously across the full range rather than at discrete heights, and the residual is limited by the reference rather than by the sensing geometry. The result is stable from room temperature to 150 °C and reproducible through repeated thermal cycles, with time of flight tracking the velocity change through heating and cooling.

Because the velocity determination responds to the liquid itself rather than to its height, it is also sensitive to changes in composition, suggesting that a single acquisition may report precursor condition alongside inventory.

9:30am TF+AP+EUV-FrM-6 ALD-Enabled Ag/ZnO Nanostructured PTFE Membranes as Flexible SERS Substrates for Trace Molecular Detection, *Halil AKYILDIZ, Sumeyye DILER INAN, Burak SOZEN*, Bursa Uludag University, Turkey

Surface-enhanced Raman scattering (SERS) is widely used for sensitive and label-free detection of molecules, with signal enhancement mainly arising from localized plasmonic effects associated with metallic nanostructures. In this study, we developed a flexible SERS substrate by combining atomic layer deposition (ALD) of ZnO with Ag nanoparticles formed on porous polytetrafluoroethylene (PTFE) membranes. PTFE membranes were first coated with ZnO by ALD, followed by the formation of Ag nanoparticles from a silver acetate solution using UV-assisted photodeposition. The SERS performance of the prepared substrates was evaluated using crystal violet

(CV) as a model analyte. CV solutions ranging from 10⁻³ to 10⁻⁸ M were deposited onto the substrates and analyzed by confocal Raman microscopy using a 532 nm excitation laser. The Ag/ZnO-coated PTFE membranes showed a clear SERS response to CV. Characteristic Raman bands at 732, 761, 809, 1175, 1373, 1538, 1588, and 1618 cm⁻¹ were observed, and their intensities decreased as the CV concentration was reduced. The characteristic bands could still be clearly identified at a CV concentration of 10⁻⁷ M, whereas they were no longer distinguishable at 10⁻⁸ M. The intensity of the characteristic band at 1175 cm⁻¹ also showed a clear dependence on CV concentration. The results show that ALD-grown ZnO can be used as an intermediate surface layer for preparing Ag-containing SERS-active PTFE membranes. Combining the flexibility and porous structure of PTFE with ALD surface modification and Ag photodeposition offers a practical approach to producing flexible SERS substrates. The prepared membranes were able to detect CV at concentrations as low as 10⁻⁷ M and may provide a useful platform for further development of flexible Raman-based chemical sensors.

9:45am TF+AP+EUV-FrM-7 Low Temperature PEALD of Epitaxial AlN on GaN, Ga₂O₃, and Al₂O₃ Surfaces, *Jeffrey Woodward, David Boris, Michael Johnson, Daniel Pennachio*, U.S. Naval Research Laboratory; *Henry Chuang*, Naval Research Enterprise Internship Program; *Michael Mathews, Emma Rocco, Katie Gann, Benjamin Sekely, Tatyana Feygelson, Jonathan Levine-Miles*, U.S. Naval Research Laboratory; *Jennifer Hite*, University of Florida; *Michael Mastro, Virginia Wheeler, Scott Walton*, U.S. Naval Research Laboratory

AlN is a wide-bandgap semiconductor with exceptional thermal conductivity, temperature stability, and piezoelectric properties, making it a promising material for high power electronics and deep ultraviolet optoelectronics in extreme environments. While plasma-enhanced atomic layer deposition (PEALD) of AlN is well-established as a promising back-end-of-line compatible process for passivation, electrical insulation, and thermal management in devices, it typically results in amorphous or polycrystalline films, which have inferior electrical and thermal properties as well as reduced chemical resistances compared to epitaxial AlN. Most reports of epitaxial AlN growth by PEALD involve the use of atomic layer annealing (ALA), in which an Ar plasma exposure is incorporated into each cycle to induce crystallization of the surface.[1] While the effectiveness of ALA is proven, its use also increases cycle duration, which significantly prolongs total process time and can promote impurity incorporation. For these reasons, the growth of epitaxial AlN without ALA is desirable, though this is challenged by the complexity of controlling the plasma properties to achieve suitable growth conditions.

In this work, we demonstrate the growth of 30-50 nm thick epitaxial AlN films on Al₂O₃, GaN, and Ga₂O₃ at 300 °C using PEALD without ALA or thermal annealing. Plasma diagnostics were used to identify favorable conditions which produce ion energy and flux characteristics comparable to those of plasmas used in ALA. The films were characterized using x-ray reflectivity (XRR), high resolution x-ray diffraction (HRXRD), in-plane grazing incidence diffraction (IP-GID), atomic force microscopy (AFM), transmission electron microscopy (TEM), x-ray photoelectron spectroscopy (XPS), and optical measurements. The growth per cycle (GPC) and density ranged from 0.90–1.03 Å and 2.998–3.173 g/cm³, respectively, with deposition on GaN resulting in the highest GPC and density. The topography of the films closely replicated that of the underlying material with roughness from 0.25–1 nm by AFM and 0.83–2 nm by XRR, indicating that the deposition was highly conformal. The epitaxial nature of the AlN (i.e., exhibiting a highly ordered crystalline structure with well-defined orientational relationship to the substrate) is confirmed by HRXRD and IP-GID, which show a single orientation with distinct 6-fold azimuthal rotational symmetry. While the AlN films on Al₂O₃ and Ga₂O₃ exhibit significant mosaicity, the AlN films on GaN exhibit low tilt disorder, as evidenced by narrow out-of-plane rocking curves with FWHM= 0.149 degrees (537 arcseconds).

[1] H. Y. Shih et al., *Sci. Rep.* **7**, 39717 (2017)

10:00am TF+AP+EUV-FrM-8 Kinetic Stabilization of Highly Dispersed Rh on MoO₃-Modified Anatase TiO₂(101), *Sineth Premaratna*, University of Washington; *Zbynek Novotny*, Pacific Northwest National Laboratory; *Charles T. Campbell*, University of Washington; *Zdenek Dohnalek*, Pacific Northwest National Laboratory

Developing approaches to stabilize highly dispersed metals on oxide supports represents one of the grand challenges in catalysis. In this context, the (101) surface of TiO₂:anatase is particularly challenging because it lacks surface defects and has a high propensity for metal clustering. We investigate the role of MoO₃ monomeric clusters, pre-deposited on

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TiO₂(101), in suppressing clustering of adsorbed Rh, using combined scanning tunneling microscopy (STM) and X-ray photoelectron spectroscopy (XPS). Rh deposited directly on bare TiO₂(101) sinters readily at 300 K, forming nm-sized Rh clusters with apparent heights of 3 Å and larger, serving as a reference system. When Rh is instead deposited on a (2×1)-ordered MoO₃/anatase(101) surface at 163 K, STM reveals significantly smaller, highly dispersed Rh species, with apparent heights of 1.8 Å, which remain stable to 450 K. These species exhibit a higher Rh 3d binding energy of 307.8 eV as compared to 307.2 eV of metallic Rh. Only after annealing to 600 K is significant ripening observed, and the cluster sizes approach those observed for Rh on bare TiO₂(101), while the Rh 3d peak shifts toward lower binding energy. The correlated STM and XPS evolution is consistent with increased final-state screening in Rh 3d peak as Rh clusters grow. Our results indicate that modification with MoO₃, combined with low-temperature deposition, kinetically traps and stabilizes highly dispersed Rh species. Ongoing work aims to identify the Mo-O-Rh binding motifs responsible for this stabilization and to determine whether they can stabilize isolated Rh atoms.

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