Advances in EUV Lithography
Room 316 - Session EUV-MoA

Advances in EUV Lithography II

Moderators: Prof. Alain Diebold, University at Albany-SUNY, **Mr. Lior Huli**, TEL, **Dr. Dustin Janes**, TEL, **Dr. Lovejeet Singh**, JSR Micro, **Dr. Kandabara Tapily**, TEL

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 (l = 157-1000 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 stochastics. 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 XPS Analysis of Inpria Metal-oxide Photoresists after Post-EUV Exposure to Oxygen and Water***, **Mark Johnson,*** Inpria Corporation*; Sonia Castellanos Ortega,* Inpria Corporation, Belgium*; Lauren McQuade, Kirsten Louthan, Michael Greer, Brian Cardineau,* Inpria Corporation

The field of Metal Oxide Resists (MOR) for EUV lithography has been pioneered by Inpria Corporation. The reactions that occur in Inpria materials following exposure to EUV photons (13.5 nm wavelength) are critical to their functioning. EUV radiolysis of these resists in UHV produces active sites that react with both oxygen and water, resulting in the differing solubility that is necessary for pattern formation during development. Previous work has shown the importance of both oxygen and humidity for photolithographic performance of similar resists [1]. It is hypothesized that both oxygen and water affect the condensation of the metal-oxo clusters and thus, their photolithographic performance [2,3]. In this study, compositional changes that occur post-EUV radiolysis, upon gas exposure to oxygen and humidity, are investigated by XPS. The post-exposure atmosphere and temperature were controlled, including the inert transfer of samples into the XPS. Some aspects and technical challenges associated with studying radiation-sensitive materials by XPS will be discussed, including the sensitivity to X-ray damage and strategies to minimize this effect. Results will be presented of Inpria MORs following EUV exposure and controlled post-treatment atmospheres with different thermal treatments in varying nitrogen, oxygen, and humidity concentrations, along with the resulting changes in composition, carbon chemistry, oxygen chemistry, and tin chemistry. A mechanistic interpretation of post-EUV chemical interactions will be proposed.

1. Ivan Pollentier, Fabian Holzmeier, Hyo Seon Suh, Kevin Dorney, Proceedings Volume 13983, Advances in Patterning Materials and Processes XLIII; 139831G (2026)
2. Sonia Castellanos, Peter De Schepper, Maireyee Bhattacharya, Jan Doise, Joren Wouters, Amrit K. Narasimhan, Brian Cardineau, Lauren McQuade, Craig Needham, Michael Kocsis, Kazuki Kasahara, and Stephen Meyers "EUV metal oxide resists: impact of the environment composition on CD during post-exposure delay", Proc. SPIE 12957, Advances in Patterning Materials and Processes XLI, 1295707 (10 April 2024); https://doi.org/10.1117/12.3010921
3. Yu Zhang, Jarich Haitjema, Xiaomeng Liu, Fredrik Johansson, Andreas Lindblad, Sonia Castellanos, Niklas Ottosson, and Albert M. Brouwer "Photochemical conversion of tin-oxo cage compounds studied using hard x-ray photoelectron spectroscopy", Proc. SPIE 10146, Advances in Patterning Materials and Processes XXXIV, 1014606 (27 March 2017); https://doi.org/10.1117/12.2257893

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 – 20 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 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 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.

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 Kaphle,* 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, Angelique 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 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 SnHx 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.

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