
# 2026 EUVL and Source Workshop

## Workshop Abstracts

EUV LITHO, INC.

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# Beyond High-NA EUV: A Dose-Window Framework for Stochastic Integrity at Future Nodes (Keynote)

Allen Gabor

*IBM Research, 1101 Kitchawan Rd, Yorktown Heights, NY 10598, USA*

As the semiconductor industry pushes to tighter pitches and lower edge-placement-error (EPE) targets, stochastic variability increasingly becomes the dominant manufacturing limiter, not nominal resolution alone. This presentation motivates why a transition beyond high-NA EUV should be framed around reducing stochastic variability and catastrophic failures. Shorter-wavelength exposure (2.5–4.5 nm) operated at low NA in the three-beam regime offers a credible path because increased aerial-image slope can offset reduced photon statistics and improve pattern fidelity at equal dose. Using a dense-pitch case study, we quantify this image-slope-versus-photon-count trade-off and introduce a practical “dose-window” framework that separates two often-conflated knobs: (i) printable dose-window coverage, which governs catastrophic stochastic failures (opens/bridges/missing features), and (ii) local CD-vs-dose sensitivity, which governs LER, LWR, and EPE even when all features remain printable. We translate this framing into measurable resist/process robustness targets and discuss system implications for mask architecture (higher magnification formats to reduce mask-3D effects) and for source/scanner dose stability. We conclude with a concise set of future-node lithography requirements and the key development gaps that must be closed, and we explain why a beyond-13.5-nm path is needed.

**Presenting Author**

Allen Gabor is an IBM Distinguished Engineer and Chief Patterning Engineer for IBM Semiconductors. He has worked in the field of lithography at Arch Chemicals, GlobalFoundries and IBM. This work has included photoresist development, CD control, overlay minimization, fundamental understanding of EPE, lithographic aware design rules and 193nm dry, 193nm immersion and EUV insertion. He received his PhD in Materials Science and Engineering from Cornell University based on his work on block copolymer photoresists. He is the author of more than 50 journal papers and holder of over 30 patents. He currently serves on the program committee for SPIE Extreme Ultraviolet (EUV) Lithography Conference and is a senior member of SPIE..

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# Mask-Wafer Co-Optimization for High-NA EUV Readiness in Advanced DRAM (Keynote)

Vineet Vijayakrishnan Nair
*Micron Semiconductor Inc., 8000 S Federal Way; Boise, ID 83707, USA*

As DRAM scaling approaches angstrom-level patterning tolerances, variability budgets have become significantly tighter than in comparable logic technologies. The introduction of EUV lithography into DRAM manufacturing has already required operation near stochastic limits while sustaining high-volume throughput. The transition to High-NA EUV further exacerbates these challenges, increasing sensitivity to mask-induced variability as feature sizes and pitches continue to shrink.

High-NA EUV is under active evaluation for advanced DRAM applications, particularly for dense contact arrays at pitches beyond the practical imaging limits of low-NA EUV. Achieving acceptable local critical dimension uniformity (LCDU) and pattern placement error (PPE) is essential for assessing High-NA EUV viability. While resist-driven stochastic effects dominate wafer-level variability in low-NA EUV, mask-related contributions—typically ~20%—are expected to increase with continued scaling, positioning mask design and write strategies as critical enablers for future DRAM nodes.

Meeting High-NA EUV requirements for DRAM will therefore require a mask-centric co-optimization approach, including systematic evaluation of mask data type, mask write process correction, mask blank selection, and mask tonality. Such optimization is essential to control variability within tightening budgets and to enable a viable transition to high-volume manufacturing.

**Presenting Author**

Vineet earned his PhD in Materials Science & Engineering from the University of California, Irvine in 2015, where his research focused on photo-electrochemistry and device fabrication. Prior to this, he completed an MS in Materials Science & Engineering from the University of Pennsylvania, and a B.Tech in Metallurgical & Materials Engineering from the National Institute of Technology, Warangal (India).

Before joining Micron, Vineet worked as a Senior R&D Engineer at Imec (Leuven, Belgium) as part of the Advanced Patterning Center, collaborating closely with ASML on Low-NA and High-NA EUV lithography pathfinding, scanner hardware, and patterning strategies. Earlier in his career, he was a Process Development Engineer at Intel, where he contributed to 10 nm and 14 nm logic technology development with a focus on lithography and process integration.

In his current position as SMTS at Micron Technology, Vineet has worked in advanced photo and EUV pathfinding, contributing to patterning strategies, mask lifetime characterization, new material enablement and High-NA EUV exploration. He is also an active contributor to the international lithography community, with multiple peer-reviewed publications and presentations at SPIE Advanced Lithography.

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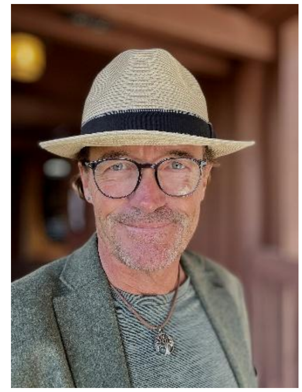
## The Amazing Longevity of Moore's Law - 50 Years of Progress in Lithography (Keynote)

Ronald Goossens[1,2]

*[1]ASML, 80 West Tasman Avenue, Building 1, San Jose, CA 95134, USA*
*[2]Elmore Family School of Electrical & Computer Engineering, Purdue University, Electrical Engineering Building, 465 Northwestern Ave, West Lafayette, IN 47907, USA*

For the past 50 years, advances in lithography have been among the key drivers of Moore's Law. All this time, these advances were guided by one simple equation that the minimum half pitch is proportional to the k1*lambda/NA. Each new technology generation was somehow enabled by advances in these three fundamental parameters. In this presentation, we will review node-by-node examples of the advances in the light source that drove the wavelength from 436nm to 365nm, then from 248nm to 193nm, and finally to 13.5nm. We will also review parallel advances in optical design and manufacturing that drove the numerical aperture of the projection optics from 0.33 in the early days of 1x g-line lithography all the way to 1.35 for ArF immersion. For EUV lithography, the NA started at 0.25, moved into production at 0.33, is now transitioning to 0.55, with serious exploration of NA of 0.75. And we will review advances in mask and resist technology, in computational lithography, and in and process control that collectively enabled reductions in k1 from around 1.00 in the early days to below 0.30 for the most critical DUV layers today. We will conclude this parade of key innovations with a look forward into what the future might bring in terms of further innovations in these areas that are the fundamental drivers for lithography.

**Presenting Author**



Ronald Goossens was born and raised in the Netherlands where he studied Physics at Utrecht University. During his Masters study, he worked on computer modeling of nucleosynthesis in stellar interiors and the impact on stellar evolution. This became the start of a life-long love affair with modeling and simulation of complex physical and chemical processes. During his years with Phillips Research, Stanford University, National Semiconductor, and NXP Semiconductor he worked on modeling of electron transport in transistors, of analog circuit behavior, and of system-level digital designs. For the last 20 years, he has worked at ASML on Computational Lithography with emphasis on control applications in semiconductor manufacturing. In early 2022, Ronald retired from full-time work. Currently, he "fills his time" as a part-time Senior Strategy Manager for ASML, as Adjunct Professor of Nanolithography at Purdue University, as a Board Member of the Boys & Girls Club of Silicon Valley, and as an avid outdoor photographer and skier.

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# Computational Microscopy for EUV Lithography (Keynote)

Laura Waller

*Electrical Engineering and Computer Sciences, The University of California Berkeley, 514 Cory Hall, Berkeley, CA 94720, USA*

Computational imaging involves the joint design of imaging system hardware and software, optimizing across the entire pipeline from acquisition to reconstruction. Computers can replace bulky and expensive optics by solving computational inverse problems, or new imaging modalities can be enabled by reconstructing invisible quantities or higher-dimensional information from carefully-designed measurement. This talk will describe applications of computational microscopy for EUV mask metrology at LBNL SHARP beamline. We show through-focus intensity images to reconstruct phase and recover 3D mask edge effects, as well as Fourier Ptychography and aberration correction methods for larger field of view at high resolution.

**Presenting Author**

Laura Waller is the Charles A. Desoer Professor of Electrical Engineering and Computer Sciences at UC Berkeley. She received B.S., M.Eng. and Ph.D. degrees from the Massachusetts Institute of Technology in 2004, 2005 and 2010. After that, she was a Postdoctoral Researcher and Lecturer of Physics at Princeton University from 2010-2012. She is a Packard Fellow for Science & Engineering, Moore Foundation Data-driven Investigator, OSA Fellow, and Chan-Zuckerberg Biohub Investigator. She has received the Carol D. Soc Distinguished Graduate Mentoring Award, OSA Adolph Lomb Medal, the SPIE Early Career Award and the Max Planck-Humboldt Medal.

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# 2µm Fiber Lasers as Efficient Next Generation EUV Drive Lasers

Tobias Heuermann[1], Mathias Lenski[2], Felix Wanitschke[2,3], Florian Bontke[2], Christian Gaida[1], Cesar Jauregui[2], Arno Klenke[2,3], Joachim Gräfe[5], Fabian Ripka[5], Jens Limpert[2,3,4], Tino Eidam[1], and Ajanthkrishna Lerch[5]

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*[4]Fraunhofer IOF, Albert-Einstein-Str. 7, 07745 Jena, Germany*
*[5]TRUMPF Lasersystems for Semiconductor Manufacturing SE, Johann-Maus-Straße 2, 71254 Ditzingen, Germany*

Power scaling of EUV power is a key driver for the semiconductor industry to increase wafer throughput and manufacturing efficiency. However, the current technology is based on a CO2-drive laser architecture, which faces challenges with heat management and is constraint to a limited wall plug efficiency. Recent theoretical and experimental studies on the efficiency scaling of EUV emission from Tin plasmas have identified, that the wavelength region around 2µm could be an attractive alternative to the traditional 10.6µm driving wavelength [1,2]. In addition, solid-state laser technology can potentially leverage the availability of highly efficient diode lasers and lower requirements on the thermal heat management due to the inherently lower quantum defect. In the recent years Tm-doped fiber amplifier technology has been identified as an efficient solid-state laser technology for the scaling of average output power in the 2µm wavelength region, reaching average output powers of more than 1kW from a single emitter. In this contribution, we will illustrate our latest results on the power scaling of Tm-doped fiber amplifiers and give prospects to scale the average output power of these sources to and beyond the kW-regime at energy levels of 10mJ from a single emitter. Furthermore, we will explore the feasibility of power scaling Tm-doped fiber lasers leveraging multicore fiber technology. This technology has recently showcased its huge potential in Yb-fiber lasers operating at 1µm wavelength, producing >3kW from a single fiber [3]. Here, we will demonstrate our first results on Tm-doped multicore fibers at 2µm wavelength and give an outlook on the future scaling potential of this technology. Our results demonstrate the potential of Tm-doped fiber amplifiers and pave the way towards efficient, low footprint drive laser technology with high wall plug efficiencies (>20%) and potential EUV-power far beyond 1kW.

[1] Y. Mostafa, et.al., “Production of 13.5 nm light with 5% conversion efficiency from 2 µm laser-driven tin microdroplet plasma,” Appl. Phys. Lett. **4** 123 (23), 234101 (2023).

[2] S. Langer, et.al., "Simulations of laser driven EUV sources—the impact of laser wavelength," 2020 EUVL Workshop (EUV Litho).
[3] Y. Khalil, et al., "3 × 3 multicore, Yb-doped fiber amplifier with 3.2 kW output power," Opt. Lett. **51**, 1677-1680 (2026).

**Presenting Author**


Tobias Heuermann received his M.Sc. from the Friedrich-Schiller University Jena in 2017. His research focuses on the power and energy scaling of Tm-doped fiber laser systems. He has made significant contributions to the field and is an author of several conference and journal publications.

Since 2024 he is a technical manager for 2µm fiber laser technology at Active Fiber Systems GmbH.

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# Power-Scalable Highly Efficient High-Harmonic Generation at 13.5 nm Using a Visible-Driving Laser (Invited)

M. Karst[2,3], M. Gebhardt[2], R. Klas[1], L. Eisenbach[1,2,3], P. Gierschke[1,2], T. Sidiropoulos[2,3], C. Gaida[4], T. Eidam[4], J. Rothhardt[1,2,3], and J. Limpert[1,2,3]

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*[4]AFS - Active Fiber Systems GmbH / Member of the TRUMPF Group Ernst-Ruska ring 17, 07745 Jena, Germany*

High-harmonic generation (HHG) at 13.5nm represents a promising route toward compact, coherent extreme-ultraviolet (EUV) sources that are candidates for e.g. semiconductor metrology. However, progress has long been limited by the inherent trade-off between conversion efficiency and average-power scalability. Here, we demonstrate a HHG architecture that breaks this constraint and delivers record performance at 13.5nm wavelength. Using a power-scalable ytterbium-based laser platform, we generate <20fs pulses at 515nm with 7W of average power, driving HHG in helium under conditions of plasma-core-induced self-guiding. This regime enables stable high-intensity propagation at a perfect ionization level for phase matching, maximizing both microscopic and macroscopic signal growth.

Under optimized conditions, we achieve 3μW of coherent EUV radiation at 13.5nm within a 2% bandwidth and a conversion efficiency of $4.4\times10^{-7}$. The average power exceeds previously demonstrated HHG-sources at this wavelength by more than an order of magnitude. We perform numerical simulations, incorporating corrected ionization rates, gas-density modeling, and full macroscopic propagation to describe the experimental results and uncover the foundations of efficient HHG.
These results establish a high-flux, power-scalable HHG architecture that directly addresses the demands of EUV metrology. Based on ytterbium laser technology we provide a scalable pathway toward compact, high-throughput coherent EUV sources.

**Presenting Author**

Robert Klas is a member of the Fiber Laser Group at Friedrich Schiller University Jena and the Fraunhofer Institute for Applied Optics and Precision Engineering (IOF) working on secondary source development. He received his Ph.D. from Friedrich Schiller University Jena in 2021. His work focuses on high-harmonic generation, nonlinear pulse compression of high-power laser systems, and fiber-laser technologies. He has contributed to the development of high-flux HHG sources in the spectral range from 20 eV to 500 eV.

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# Development of a High-Power 3–4 μm Mid-Infrared Laser for High-Efficiency EUV Light Sources (Invited)

Ryo Yasuhara

*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki City, GIFU Prefecture 509-5292, Japan*

The conversion efficiency from the driving laser to EUV light depends strongly on the laser wavelength. Radiation-hydrodynamic simulations have shown that an optimum wavelength exists between the 1 μm band and 10.6 μm. Within this range, the 3 μm - 4 μm bands have been identified as promising candidates for high EUV conversion efficiency. However, practical high-power lasers suitable for EUV generation studies are not yet available in these wavelength ranges, and experimental validation of the simulation results has therefore remained limited. As a result, the wavelength dependence of EUV generation efficiency in the mid-infrared region has not yet been sufficiently examined under conditions relevant to laser-produced plasma sources. This presentation will discuss the development of solid-state lasers in the 3 μm and 4 μm bands for EUV generation at laser power densities of 10^10 W/cm^2 and above. It will also present the background for selecting these wavelength bands and their relevance to the experimental assessment of wavelength-dependent EUV conversion efficiency.

**Presenting Author**

Ryo Yasuhara is a professor at the National Institute for Fusion Science (NIFS) and SOKENDAI, and Director of the Fusion Science Interdisciplinary Coordination Center at NIFS. He earned his Ph.D. from Osaka University in 2008 and has built a career spanning industry and academia, including experience at Hamamatsu Photonics and NIFS. His research focuses on lasers, plasma science, and nuclear fusion.

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# Scaling Efficiency and Power in $CO_2$ Drive Lasers for EUV (Invited)

Jens Brunne

*TRUMPF Lasersystems for Semiconductor Manufacturing SE, Johann-Maus-Strasse 2, 71254 Ditzingen, Germany*

Today, the CO2 drive laser is the workhorse behind EUV sources in high-volume manufacturing. Scaling of drive-laser power enabled the HVM breakthrough, lifting source power from 250 W to 600 W. To unlock the next performance node, we have developed a high-efficiency CO2 laser platform designed to propel the EUV roadmap in the coming decade. The architecture combines higher intrinsic gas-laser efficiency with a path to elevated repetition rates, aligning with the 100 kHz operation announced by ASML for a 1000W source. Beyond the power boost, the platform delivers major improvements in serviceability, reinforcing today's proven reliability while simplifying service for sustained HVM operation

**Presenting Author**

Jens Brunne is the Head of Systems Engineering at TRUMPF, overseeing all aspects of Drive Laser technology for EUV. He is responsible for the performance of current systems and the technological development of future generations. Jens holds a PhD in Microsystems Engineering and brings over a decade of experience in various roles related to the development of CO2 drive lasers.

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# A Scalable 2 µm Laser Platform for Next Generation EUV Light Sources (Invited)

Joachim Gräfe

*TRUMPF Lasersystems for Semiconductor Manufacturing SE, Johann-Maus-Strasse 2, 71254 Ditzingen, Germany*

Increasing performance requirements in EUV lithography continue to push the limits of drive laser technology. To address these demands, TRUMPF is developing a scalable 2 µm laser platform that integrates advanced amplifier concepts, flexible pump architectures, and multiple beam combination approaches. This platform provides tailored pulse formats, high brightness, and stable long-term operation across a wide range of laser driven EUV generation schemes.

The modular architecture supports configurations optimized for cost efficient implementations, maximum performance scaling, or highest wall plug efficiency. It accommodates various EUV source concepts, offering continuous wave operation as well as short pulse formats, enabling application specific tuning of power, brightness, and temporal characteristics.

The presentation summarizes the current status and roadmap of TRUMPF's 2 µm technology stack, including Thulium doped fiber and solid-state power amplifiers, advanced pump schemes, and multiple combining strategies. We discuss the design principles enabling efficient power scaling and robust industrial reliability at high average power, positioning the 2 µm platform as a flexible foundation for next generation EUV light source development.

**Presenting Author**

Joachim Gräfe is a Project Cluster Manager at TRUMPF driving the development of an innovative 2 μm laser platform for laser-driven EUV sources. He also has several years' experience on CO2 drive lasers.

He previously held a research group leader position at the Max Planck Institute for Intelligent Systems, where his work focused on time-resolved X-ray microscopy, ultrafast magnetization dynamics, and magnonics. His academic research has significantly contributed to nanoscale imaging techniques and the understanding of dynamic magnetic phenomena relevant to future information technologies.

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# High Energy Solid-State λ ≈ 2 μm Laser Drivers for Efficient EUV and Plasma Sources (Invited)

Emily Sistrunk[1], Patrick Poole[1], Mark Sherlock[1], Sigfried Glenzer[2], Zbynek Hubka[1], Leily Kiani[1], Brendan A. Reagan[3], Issa Tamer[1], Scott Wilks[1], Andrew Yandow[1], and Jackson Williams[1]

*[1]Lawrence Livermore National Laboratory, Livermore, CA, USA*
*[2]SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
*[3]Colorado State University, Ft. Collins, CO, USA*

An efficient and compact diode-pumped, solid-state λ ≈ 2 μm Tm:YLF laser has been demonstrated that produces joule-class pulses in two distinct models: sub-picosecond pulses exceeding 1 TW peak power using chirped pulse amplification [1] and >20 J, nanosecond duration pulses [2]. We report on ongoing efforts to design and construct an upgraded Tm:YLF laser architecture that supports both pulse formats, while delivering energetic bursts of 1 kHz pulse trains. This table-top laser system will be installed in a dedicated facility at LLNL with the purpose of producing extreme ultraviolet (EUV) and hard x-rays sources using the laser in sub-picosecond and nanosecond modes, respectively. We will discuss the implementation of design features intended to increase EUV conversion efficiency and the status of modeling of the high-energy, λ ≈ 2 μm laser interaction.

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and funded by the Office of Science Microelectronics Science Research Center under Grant SCW1907. LLNL-ABS-2016943

[1] I. Tamer, et al., "Demonstration of a 1 TW peak power, joule-level ultrashort Tm:YLF laser," Opt. Lett. 49, 1583-1586 (2024).
[2] I. Tamer, et al., "1 GW peak power and 100 J pulsed operation of a diode-pumped Tm:YLF laser," Opt. Expr.30, 46336-46343 (2022).

**Presenting Author**

Emily Sistrunk Link is a research physicist at Lawrence Livermore National Laboratory (LLNL) and the Advanced Photon Technologies Group Leader for Laser Development within the National Ignition Facility & Photon Science Directorate. Dr. Sistrunk leads the development and execution of new laser technologies for high average power lasers and their applications for basic science and national security applications.

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# Compact Free-Electron Lasing at BELLA Center's Laser-Plasma Accelerator (Invited)

Finn Kohrell, Tehya Andersen, Jeroen van Tilborg, and Sam Barber

*BELLA Center, LBNL, 1 Cyclotron Rd., Berkeley, CA 94720, USA*

Since 2021, three separate groups working on laser-plasma accelerators (LPAs) have demonstrated that these novel, compact accelerators can deliver electron beams of the quality required to drive free-electron lasers (FELs). Most recently, the BELLA center has shown results at 400nm FEL emission not only exhibiting greater than 1000-fold coherent gain [see S. Barber et al. PRL 135, 055001 (2025)], but through exceptional long-term stability of the LPA maintaining this level of FEL performance for over 8 hours of continuous operation [F. Kohrell et al, PRAB, in press (2026)]. In this talk, I will present these recent results, and provide an outlook on our roadmap to further increase FEL gain, stability, and photon energy to unlock compact, reliable FEL operation in the EUV regime.

*This work is supported by the Office of Science of High Energy Physics (HEP) and Basic Energy Sciences (BES) under Contract No. DE-AC02-05CH11231.*

**Presenting Author**

Finn Kohrell is a Postdoctoral Researcher at the BELLA Center for Laser-Wakefield Acceleration at the Lawrence Berkeley National Laboratory (LBNL). He received his PhD in Physics from the University of Hamburg (UHH) in 2025 for his work on the FEL project at the BELLA Center at LBNL. His current research interests and focus is the improvement of long-term stability of high-power laser system, laser-plasma interaction, as well as FEL physics.

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# Laser–Plasma Accelerators and Their Potential to Drive EUV Light Sources

Manuel Kirchen

*Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*

Driven by increasing demands on power and wavelength scalability, accelerator-based concepts are gaining renewed attention as drivers of EUV light sources for lithography, as reflected in growing industrial activity. In this context, laser–plasma accelerators (LPAs) provide a compact route to high-energy electron beams, leveraging accelerating fields far beyond those of conventional radio-frequency technology. This talk provides an introduction and review of the field and discusses the opportunities and challenges of LPAs as compact sources of energetic electron beams. Particular emphasis is placed on average power scalability, wall-plug efficiency, and the potential of alternative laser architectures for driving LPAs, such as ytterbium-based systems. This perspective is complemented by an overview of the comprehensive research program at DESY to mature LPA technology and demonstrate its application for photon science facilities—developments that, beyond their scientific motivation, pave the way for industrial applications.

**Presenting Author**

Manuel Kirchen is a Staff Scientist at DESY, a leading European accelerator laboratory, and has over a decade of experience in laser-plasma accelerator development. He leads a team and research program on high-average-power laser-plasma accelerators, addressing key scientific and technological challenges toward their practical realization. He began his career with particle-in-cell code development for relativistic plasma simulations and has since developed broad expertise in high- power laser systems, laser-plasma interactions, free-electron laser physics, and data-driven accelerator operation.

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# TAU Systems Inc.: Bringing Laser-Powered Accelerator Systems to the Commercial Market (Invited)

Stephen Milton

*TAU Systems, Inc. 201 W 5th Street, Suite 1100, Austin, TX 78701, USA*

The compact laser-powered accelerator (LPA) has reached a level of maturity that it can now be offered as a commercial product. Capable of readily accelerating electrons to GeV levels the LPA can be used as a base for many systems requiring high-energy electrons. TAU Systems is the first company to offer LPAs for a variety of applications. In this short presentation we will provide an overview of TAU Systems, the LPA and its capabilities, and some of the many applications the LPA can be used for.

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# Development of Capping Films Integrated with Mask Process for 1.X nm Node EUV Blanks (Invited)

Ayumi Moriya, Hibiki Kishida, Kazuhiro Hamamoto, Masanori Nakagawa, Yohei Ikebe, and Takahiro Onoue

*HOYA Group LSI Division, 3280 Nakamaru, Nagasaka, Hokuto, Yamanashi 408-8550, Japan*

For next-generation EUV lithography, absorber materials have been mainly developed in EUV mask blanks. Low-n materials are candidates for alternative absorber materials and expected to improve NILS and dose compared to conventional Ta-based absorbers. At the same time, design of capping films suitable for the absorbers is becoming significant. Capping films play a role in protecting multilayer from mask making processes and undergo patterning by dry etching, mask cleaning, and pattern repairing. EUV reflectivity on capping films is one of the critical parameters for exposure characteristics, however those mask processes can affect the surface/interface of films, resulting in EUV reflectivity change. Furthermore, the degradation of films below absorbers tends to be outstanding for lots of alternative absorber materials due to their slower etching rates, presenting new challenges in mask making process. In particular, during the dry etching, exposure of plasmas to capping films not only causes EUV reflectivity change but also raises concerns about deterioration of film durability. To suppress the film damage, improvement of capping films or optimization of the etching process are required. In this presentation, we will report our development status of capping films for next-generation EUV mask blanks and discuss more damage-free etching process.

**Presenting Author**

Ayumi Moriya joined HOYA in 2023 and is currently an engineer engaged in the development of EUV mask blanks. Her primary expertise is in etching processes. She received her MS degree in Physics from Tohoku University in 2023.

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# Accurate Long Range Compact Modeling for Low-NA and High-NA EUV Mask Solutions (Invited)

Zac Levinson, Chih-I Wei, Philip C. W. Ng[2], Ulrich Welling, Cheng-Huei Lin[2], Chao-Heng Chen, Ming-Yun Chen[2] Ulrich Klostermann[3], Michael Lam, and Kostas Adam

*Synopsys Inc., USA*
*[1]Synopsys Belgium BV*
*[2]Synopsys Taiwan Co., Ltd*
*[3]Synopsys GmbH*, Germany

Lower-K1 EUV lithography presents challenges for mask solutions operations (e.g., OPC, ILT and LRC) because of the increasing demand for highly accurate full-chip and full-reticle compact models. In this work we investigate compact modeling for a lower-K1 long range effects. In one example we study a high-NA EUV lithography process with an 18 nm minimum pitch line-space array structure with a minimum CD of 9 nm after-development (ADI). These small dimensions require an error budget of under 1 nm allocated across all sources of variation, including OPC model inaccuracies. The use of a novel metal-oxide resist (MOR) and development process for low-NA or high-NAEUV introduces further complexity in metrology, imaging, and in the calibration of full-chip compact models. For example, long-range chemical flare effects which extend beyond the optical influence of EUV imaging, must also be incorporated into the modeling framework to ensure sufficient model accuracy. We observe that machine learning (ML)-assisted long-range aware OPC modeling is a promising solution for achieving the required ADI CD prediction accuracy. We demonstrate the importance of carefully optimizing the ML architecture and show that our approach can meet the stringent precision requirements for OPC in advanced technology nodes using lower-K1 low-NA or high-NA EUV.

[1] Chih-I Wei, et. al. Machine Learning Enhanced Optical Proximity Correction Modeling for High-NA EUV Lithography. Proc. Of SPIE 2026, to be published.

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# In Situ Monitoring During Mo-Si Mulyilayer Deposition for EUV Mask Blanks : Concept and Simulation (Invited)

Binyamin Rubin

*Veeco Instruments, 1 Terminal Drive, Plainview NY 11803, USA*

In-situ monitoring of EUV multilayer deposition is a key enabler for tighter control of central wavelength, reflectance, and long-term deposition tool stability. Practical solutions must balance actinic relevance, vacuum compatibility, and cost. This talk surveys a spectrum of in-situ monitoring options, including (1) process proxy sensors used in production-like environments (QCM, optical emission spectroscopy); (2) at-wavelength approaches that interrogate the EUV band (13.5 nm and beyond) using compact EUV sources combined with spectrally resolving diagnostics; and (3) higher-fidelity research techniques such as in-situ XRR/GISAXS and EUV scatterometry. While optical monitoring is widely and successfully used for UV–Vis–IR coating control, it is not directly transferable to the EUV regime due to absorption and source constraints. However, important lessons carry over, particularly in monitoring architectures, signal conditioning, and real-time analysis and control algorithms. We conclude with recommended monitoring architectures matched to development and manufacturing needs.

**Presenting Author**

Dr. Binyamin is Technology Manager for Advanced Deposition and Etch Division of Veeco Instruments. Binyamin has over 15 years of experience in thin film deposition technologies. Before joining Veeco he was engaged in development and testing of ion thrusters for space propulsion. At Veeco he worked on development of ion beam deposition and etch systems, including optical monitoring systems for in-situ process control.

For the presented material, Binyamin expresses special thanks to his co-workers Kenji Yamamoto, Dr. Katrina Rook, and Dr. Antonio Checco.

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# Harnessing the Power of Actinic Metrology for EUV Masks (Invited)

Stuart Sherwin

*EUV Tech, 2830 Howe Road, Suite A, Martinez, CA 94553, USA*

As feature sizes on EUV photomasks continue to shrink to accommodate higher resolution patterns, sub-resolution assist features, and sub-resolution gratings, mask process control and metrology are being pushed to their limits. While mask pattern fidelity can be monitored with other metrology techniques, the ideal probe for an EUV mask is EUV radiation itself. Actinic reflectometry to guarantee consistent multilayer reflectivity has been widely accepted as indispensable for EUV photomask process control due to its unique sensitivity to the exact physical mechanisms on the mask relevant to lithographic performance. The EUV Tech ENK tool enables additional modalities of actinic metrology to probe critical properties of photomasks with EUV radiation, including EUV refractive index, multilayer and absorber film modeling, and scatterometry-based CD metrology. These applications can accelerate innovation in materials, film processing, and mask patterning, by providing unique actinic modalities previously available only at scientific facilities directly to the manufacturers and users of EUV photomasks.

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# Advancements in ZEISS EUV Projection Optics: Enhancing Productivity and Enabling Shrink (Invited)

Sebastian Brueck, Thilo Pollak, and Paul Graeupner

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Extreme Ultraviolet (EUV) lithography is the key technology for high-volume semiconductor manufacturing, particularly for smaller feature sizes. ZEISS is at the forefront of this evolution, providing advanced projection optics with numerical apertures (NA) of 0.33 and 0.55 for the NXE:3800E and EXE:5200B ASML scanners. The 0.33 NA optics have established themselves as the backbone of high-end chip manufacturing, delivering exceptional optical performance and productivity. Meanwhile, the newly introduced 0.55 NA system demonstrates remarkable optical capabilities from its inception and is now being integrated into fabs for high-volume manufacturing (HVM).

In this presentation, we will highlight how the continuous enhancement of key optical performance parameters in the 0.33 NA optics has been instrumental in driving HVM success. Additionally, we will discuss the technological and manufacturing challenges encountered with the 0.55 NA optics and the innovative solutions implemented to achieve outstanding optical performance in the initial production units. Finally, we will provide an overview of the performance of the current optics populations of both product lines, underscoring this success story.

**Presenting Author**

Dr. Sebastian Brueck is the Lead Systems Engineer for High-NA Optics at Carl Zeiss SMT GmbH. Prior to joining ZEISS in 2012, he specialized in soft-X-ray scattering and the characterization of thin film interfaces. At ZEISS, Sebastian initially worked in research and development for EUV metrology and coatings, contributing to advancements in measurement techniques and coating technologies. He then focused on manufacturing processes for EUV optics. Today, Sebastian and his team are developing processes for manufacturing the newest generation of High-NA EUV optic components.

P31

# New Developments at the Synchrotron Ultraviolet Radiation Facility (SURF III) (Invited)

Stephanie L. Moffitt

*National Institute of Standards and Technology, Gaithersburg, MD 20899, USA*

The National Institute of Standards and Technology (NIST) is continuing its decades-long track record of supporting EUVL metrology with the development of several new projects at the Synchrotron Ultraviolet Radiation Facility (SURF III).

Recently, a novel system employing 4-bounce chevrons as compensators in a dual rotating compensator Mueller matrix ellipsometer has been assembled and installed on the wide spectral range beamline, beamline 3. Initial testing of the system has demonstrated polarization control at multiple vacuum ultraviolet wavelengths (VUV). Sensitivity analysis has shown that enabling polarization control at shorter wavelengths can provide improved measurements of certain nanoscale geometries [1].

Work has also begun to ensure SURF III is ready to meet the growing needs of the EUVL industry. The reflectometry program has begun preparations for a new facility with improved reliability and throughput. The detector calibrations program has initiated several new developments which will expand measurement capacity and improve measurement uncertainty.

[1] A. Chew, B. M. Barnes, E. L. Shirely, and T. A. Germer, "Ellipsometry in the EUV regime," *Proc. SPIE* 13426, 1342609 (2025).

**Presenting Author**

Stephanie L. Moffitt is a beamline scientist working on developing metrology at NIST's Synchrotron Ultraviolet Radiation Facility (SURF III). Her current work involves projects addressing radiometry, scatterometry, reflectometry and optics lifetime testing. She received her Ph.D. in Materials Science and Engineering from Northwestern University. Since 2011, she has been using synchrotron beamlines to study the properties of materials.

P32

# Progress on the NIST Deployable Absolute EUV Radiometer (Invited)

Brian J. Simonds, Bradley Pelz, Jack R. Tanner, Nathan Tomlin, Chris Yung, Steve Grantham, Stephanie Moffitt, Rob Vest, John Lehman, and Michelle Stephens

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Absolute radiometric power in the extreme ultraviolet is commonly measured by photodetectors that rely on routine calibrations to a primary standard. Regular use and degradation of these detectors suggest that they be frequently calibrated, yet calibrations at synchrotron facilities can have wait-times on the order of weeks or months. A solution is to have a deployable, primary standard that could routinely calibrate an EUV photodetector at the point-of-use employing the end user's EUV source. NIST is developing a carbon nanotube-based electrical substitution radiometer (ESR) [1-2] precisely for this purpose. We have completed construction of a prototype detector and have validated its accuracy by comparing it against other primary standards using visible laser sources—an advantage of using the spectrally flat broadband absorbing nanotubes as the absorber. We have also confirmed the ultrahigh vacuum compatibility of the device and associated hardware. The control and readout electronics have been successfully demonstrated using a single, ruggedized FPGA device with an emphasis towards deployability. Testing at EUV wavelengths is scheduled for the near future at the NIST SURF synchrotron facility with an eventual comparison against the cryogenic radiometer primary standard.

[1] Simonds et al., A deployable EUV radiometer with direct SI-traceability, *SPIE Advanced Lithography + Patterning* 2026 (in print)

[2] Tomlin et al., Overview of microfabricated bolometers with vertically aligned carbon nanotube absorbers, *AIP Advances* **10**, 055010 (2020)

**Presenting Author**

Brian is a physicist in the Applied Physics Division at the National Institute of Standards and Technology in Boulder, CO, where he has been since 2014. He specializes in high-power laser radiometry and metrology of intense laser-material interactions. He also has experience with photovoltaics, laser processing of semiconductors, and laser metal manufacturing. He received his PhD in applied physics in 2012 from the Colorado School of Mines and a bachelors-of-science degree in physics from Illinois Wesleyan University in 2005.

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# Actinic EUV/Blue-X Characterization for Advanced Materials and Lithography Applications

Jiho Kim[1], Geonhwa Kim[1], Hyuk Jin Kim[1], Nam Hyeon Kim[1], and Sangsul Lee[1,2]

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This talk presents actinic EUV/Blue-X characterization of advanced materials for semiconductor and lithography applications. These capabilities enable a wide range of actinic EUV/Blue-X characterization studies for semiconductor materials. We conduct such studies on EUV/Blue-X-related materials such as photoresists, pellicles, and masks using actinic EUV/Blue-X light sources, including synchrotron radiation and high-harmonic generation (HHG) light sources. In this presentation, we introduce our recent studies on carbon nanotube (CNT) pellicles and silicon oxide photoresists using EUV and Blue-X beams. We evaluate the transmission, reflection, scattering, and thermal stability of CNT pellicles. Furthermore, we discuss latent images with 10 nm resolution and infrared spectra of silicon oxide photoresists.

**Acknowledgments.** This work was supported by National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF-RS-2024-00443105, NRF-2022M3H4A308806913)

[1] SPIE ALP 2026, Paper 13979-65 (to be published)
[2] SPIE ALP 2026, Paper 13981-109 (to be published)
[3] SPIE ALP 2026, Paper 13981-126

**Presenting Author**

Jiho Kim is a staff scientist for the EUV beamline in Pohang Accelerator Laboratory (PAL). He earned his Ph.D. in Physics from the University of Seoul (UOS) and completed postdoctoral research at the 12D IRS and PAL-EUV beamline in PAL. Currently, he is designing the EUV beamline facilities. Also, he is focusing on testing and evaluating materials and devices for extreme ultraviolet lithography (EUVL), including EUV photoresists, masks, and pellicles.

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# SparkLight: A New Platform for Laser-Produced Plasma Research in Support of Next-Generation EUV Lithography (Invited)

A. Diallo, S. Musikhin, K. Lezhnin, A. Griffith, S. Yatom, and A. Morozov

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SparkLight generates tin plasmas by irradiating a continuously moving tin-coated wire with a 1064 nm Nd:YAG laser. The facility integrates three complementary diagnostics: EUV emission spectroscopy, laser interferometry, and coherent Thomson scattering. Thomson scattering is implemented with a compact design based on a Wollaston prism, volume Bragg grating notch filters, and a single-grating spectrometer — enabling space- and time-resolved measurements of electron density and temperature while rejecting stray light and plasma self-emission.

We highlight two foundational contributions within the SparkLight program: a multi-diagnostic experimental characterization of laser-produced tin plasmas, demonstrating that the integrated platform simultaneously resolves the plasma parameters governing both spectral purity and EUV conversion efficiency; and radiation-hydrodynamics and collisional particle-in-cell simulations of fast ion debris generation, examining how laser wavelength and target material modulate ion debris spectra and assessing the predictive fidelity of radiation-hydro codes across operating regimes. Together, these experimental and simulation efforts deliver a self-consistent picture of laser-plasma coupling, EUV emission, and debris dynamics.

Beyond its current tin wire target, SparkLight is designed as a flexible platform to explore next-generation source materials including beyond-EUV (BEUV) target materials, which emit efficiently near 6.7 nm and represent a roadmap technology for sub-5 nm lithography nodes. The SparkLight multi-diagnostic suite will characterize EUV and BEUV yield, charge state distributions, and plasma evolution across these novel targets.

**Presenting Author**

Ahmed Diallo is a Principal Research Physicist at the Princeton Plasma Physics Laboratory (PPPL), where he leads the EUV source research program and directs the SparkLight facility. His research encompasses laser-produced plasmas, advanced plasma diagnostics, and fusion science. He leads the inaugural Division in Enabling Technologies for Energies and Science (ETES). He received his Ph.D. in physics and has extensive experience in plasma spectroscopy, Thomson scattering, and high-energy-density plasma experiments.

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# Positive-Tone Hybrid EUV Resists Synthesized by Vapor Phase Infiltration (Invited)

Nikhil Tiwale

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Hybrid EUV resist development has been spearheaded by variety of negative-tone resists,[1,2] whereas the development of positive-tone hybrid resist system is lagging. We have been developing ex-situ vapor phase infiltration route for synthesizing positive-tone hybrid resists, that have demonstrated ultra-high etch selectivity for Si patterning and EUVL patternability.[3,4] We expand the approach to metal-only infiltration [5] and alkaline developable high sensitivity resist [6] for residue-free patterning along with improved EBL/EUVL sensitivity. The talk will discuss details of the underlying infiltration chemistry. Furthermore, recent experimental results of high-resolution line-space and contact-hole EUVL patterning will be showcased.

References – [1] Saifullah, Tiwale and Ganesan, JM3, **21**, 1 (2022); [2] Saifullah, Tiwale et al. ACS Nano **18**, 24076 (2024); [3] Tiwale, Nam et al. J. Mater. Chem. C **7**, 8803 (2019); [4] Subramanian, Tiwale, Nam et al. Adv. Mater. Interfaces **10**, 2300420 (2023); [5] Chowdhury, Tiwale, Nam et al. Chem. Mater. **38**, 1715 (2026); [6] Tiwale, Nam et al. in preparation.

**Presenting Author**

Dr Nikhil Tiwale is Assistant Scientist in Electronic Nanomaterials Group at CFN-BNL. He pursued postdoctoral research working with Dr. Chang-Yong Nam at CFN-BNL, employing infiltration synthesis for developing hybrid resists for advanced nanolithography and fabrication of nano(opto)electronic devices. He obtained his PhD from University of Cambridge in 2017 on EBL direct-write ZnO nanodevices, under the supervision of Prof. Sir Mark Welland.

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# EUV Research Activities and Infrastructure Development at BNL (Invited)

Chang-Yong Nam[1] and Jiyoung Kim[2]

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*[2]Department of Materials Science and Engineering, The University of Texas at Dallas, Richardson, TX 75080*

In this talk, I will provide an overview of EUV research activities and infrastructure development at Brookhaven National Laboratory (BNL). Our EUV research has been primarily anchored in the DOE Accelerate Initiative project, "Angstrom Era Semiconductor Patterning Material Development Accelerator," which involves five institutions and will conclude at the end of August 2026 after a three-year period, as well as in internally funded efforts. I will highlight a few key achievements, including EUV-electron sensitivity correlation, new organic-inorganic hybrid resists synthesized by molecular atomic layer deposition (MALD) with sub-12 nm EUV patterning, and computational EUV interference lithography for arbitrary pattern formation. Finally, I will briefly discuss the current progress in developing an EUV interference lithography patterning end-station at BNL. This capability is being developed in partnership with the Center for X-ray Optics (CXRO) at Lawrence Berkeley National Laboratory (LBNL) and aims to achieve sub-10 nm patterning resolution, high throughput, and a pattern field area commensurate with advanced characterization methods such as critical-dimension small-angle X-ray scattering.

**Presenting Author**

Chang-Yong Nam is a Senior Scientist and the Group Leader of the Electronic Nanomaterials Group at the Center for Functional Nanomaterials (CFN) of Brookhaven National Laboratory (BNL). He is also an Adjunct Professor of Materials Science and Chemical Engineering at Stony Brook University. Dr. Nam received his Ph.D. in Materials Science and Engineering from the University of Pennsylvania (2007), M.S. in Materials Science and Engineering from KAIST (2001). and B.E. in Metallurgical Engineering from Korea University (1999). Dr. Nam joined Brookhaven in 2007 as a Goldhaber Distinguished Fellow and has risen through the ranks to Scientist in 2016. Dr. Nam's research is focused on: (a) Development of ALD methods towards microelectronics and energy applications; (b) Materials processing and device physics in low dimensional semiconductors. His awards include, BNL Science & Technology Award (2024). DOE Accelerate Initiative Award (2023), Battelle Inventor of the Year (2022), Winner of DOE National Labs Accelerator Pitch Event (2021), BNL Spotlight Awards (2018, 2011), and Goldhaber Distinguished Fellowship (2007)

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# Defect-Free EUV Patterning of Metal Oxide Resists using $Cl_2$/Ar LET Plasma Dry Development for High-Fidelity Etch Transfer

Jiwon Kim[1,4], Ji-Hoo Seok[1,4], Kwangsub Yoon[1,3], Taeho Lee[4], Chin Wook Chung[2,4] and Jinho Ahn[1,2]

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*[4]CH[3]IPS (Center of Hyperscale, Hyperfunction, Heterogeneous Integration Pioneering Semiconductor Technology), Seoul, 04763, Republic of Korea*

Extreme ultraviolet (EUV) lithography is essential for high-resolution patterning in next-generation semiconductor manufacturing; however, conventional chemically amplified resists (CARs) suffer from low EUV absorption and insufficient etch durability. Metal oxide resists (MORs) address these issues but face critical challenges in wet development, including pattern collapse in fine-pitch regimes due to capillary forces and metal residues causing after-etch defects.

In this study, we propose a plasma-based dry development process using $Cl_2$/Ar chemistry under low electron temperature (LET) conditions. $Cl_2$ enables formation of volatile tin-chloride (SnClx) by-products, allowing efficient removal of the MOR matrix without metallic residues. By precisely controlling the grid bias, electron temperature is reduced, suppressing ion-induced damage while promoting radical-driven reactions. As a result, collapse-free patterning of 10–50 nm line-and-space and pillar structures is achieved, with low line edge roughness (~3 nm) and improved CD uniformity relative to wet development. To evaluate residue effects on subsequent processes, pattern transfer into $SiO_2$ was performed using $CHF_3$/Ar etching. Wet-developed samples showed defects due to residual metal species acting as etch masks, whereas dry development suppressed these effects, enabling defect reduction and high-fidelity pattern transfer.

These results demonstrate that LET plasma-based dry development is a promising strategy for high-resolution, defect-free patterning.

**Presenting Author**

Jiwon Kim is a Ph.D. candidate in the Department of Materials Science and Engineering at Hanyang University. Her research primarily focuses on plasma-based dry development processes for EUV patterning, with a specific emphasis on suppressing stochastic defects and enhancing pattern fidelity in metal oxide resists (MOR) for next-generation semiconductor manufacturing.

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# Amorphous Zeolitic Imidazolate Frameworks (aZIF) as Resists for EUV and BEUV Lithography (Invited)

Michael Tsapatsis

*Johns Hopkins University, Baltimore, MD 21218, USA*

Advancements in lithography have focused on shorter exposure wavelengths and new resist types to enable finer feature patterning, resulting in denser integrated circuits and more efficient chips. However, current resist technologies may not meet future demands outlined in technology roadmaps for sub-nanometer nodes, which target features down to 5 nm and below. We introduced a class of amorphous metal organic frameworks (amorphous zeolitic imidazolate frameworks: aZIFs) as resists for electron-beam lithography (EBL), extreme ultraviolet lithography (EUVL: 13.5 nm), as well as for lithography using smaller wavelengths, beyond EUV (BEUV: 6.7 nm). The sensitivity and tone (negative or positive) of aZIFs can be tuned by the choice of metal and imidazole, and by the selection of appropriate vapor or liquid development methods. aZIF resists can be deposited by ALD/MLD, as well as by spin-on methods, with excellent control of compositions, thickness, and wafer-scale uniformity.

In this talk, I will give a historical perspective of ZIFs starting from Professor Yaghi's group discoveries that established this class of materials, describe their solvothermal and vapor phase synthesis, their solubility in aqueous solvents, and their sensitivity to low energy electrons, which led us to propose them as lithographic materials (Angew. Chem. Int. Ed. 57, 13592-13597 (2018)). The current status of development of aZIF resists will then be described based on our recently published work (Chemistry of Materials37(21), 8548–8567 (2025), Nature Chemical Engineering 2, 594-607 (2025)), followed by a description of our ongoing efforts to exploit the rich compositional space of a ZIFs to improve their sensitivity and resolution.

**Presenting Author**

Michael Tsapatsis is a Bloomberg Distinguished Professor of Chemical and Biomolecular Engineering at Johns Hopkins University (JHU) with a joint appointment in the Applied Physics Laboratory. His research group's accomplishments include development of hierarchical mesoporous zeolite catalysts, oriented molecular sieve films, molecular sieve/polymer nanocomposites for membrane applications, crystal structure determination of adsorbents that are now used in a commercial process, and synthesis of precisely sized oxide nanoparticles that have been commercialized. He was elected to the US National Academy of Engineering (2015) for contributions to the "design and synthesis of zeolite-based materials for selective separation and reaction." In the last decade, he is developing novel uses of metal-organic thin films for applications as separation membranes, and in the microelectronics industry as resists for lithography.

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# Dry Patterning Solutions Enabling High-NA Lithography for Accelerated Feature Scaling (Invited)

Anuja De Silva

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With each technology generation, device dimensions continue to shrink, driven by ongoing advances in lithography. Extreme ultraviolet (EUV) lithography at a 13.4 nm wavelength is now in high-volume manufacturing, while high-numerical-aperture (high-NA) EUV is under active development. The introduction of high-NA EUV with the TWINSCAN EXE:5000 enables feature scaling below 28 nm pitch using a single EUV exposure, placing new demands on photoresist materials and patterning processes. Realizing the full benefits of high-NA EUV requires innovations that extend beyond conventional solution-processed EUV resists.

All-dry EUV resist technologies provide differentiated process knobs that enable enhanced performance relative to traditional resist systems. Lam's Aether® dry resist technology has been adopted in high-volume manufacturing, overcoming long-standing trade-offs among resolution, sensitivity, line-edge roughness and defectivity while delivering full productivity entitlement for 0.33 NA EUV lithography. In this work, we demonstrate continued progress in dry resist development to address the specific challenges of high-NA EUV. In particular, expanding depth of focus (DoF) while maintaining high pattern fidelity at low dose is critical at 0.55 NA. We present 3D engineered dry resist films that enable through-thickness composition tuning and profile modulation, providing scalable benefits as pattern pitch continues to shrink. Validation of 3D engineered resist concept through high NA patterning at pitch 20nm and below will be demonstrated.

**Presenting Author**

Anuja De Silva is a Technical Director at Lam Research, with expertise in new materials and processes for advanced patterning and EUV lithography. She received her PhD from Cornell University and has made significant contributions to the field through both industry and academic leadership. Anuja serves as a co-chair of the *SPIE Advanced Lithography—Advances in Materials and Processes* conference and is an editor for *JM3*. She has authored over 100 publications and patents spanning advanced lithography and patterning technologies.

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# Navigating Chemical Stochasticity in EUV Lithography: CHiPPS Materials Platforms and Metrology (Invited)

Ricardo Ruiz

*Lawrence Berkeley National Laboratory, Berkeley CA, USA*

As EUV lithography progresses toward hyper-NA or beyond EUV, stochastic variations within resist materials increasingly limit pattern fidelity. At CHiPPS, our goal is to systematically identify and probe the physical and chemical contributors to these variations, while building fundamental knowledge that can guide future material and process design.

We connect EUV exposure physics to stochastic outcomes by studying how ionization-driven radiolysis initiates chemical transformations that propagate through resist composition, molecular architecture, polymer sequence, and networking chemistry. Our activities include exploring EUV-relevant resist platforms, such as sequence-defined polypeptoid materials, and MLD-based approaches that enable controlled tuning of resist composition, sequence, polydispersity, and network density. We also investigate bottom-up strategies based on self-assembly and area-selective deposition to improve roughness and uniformity. Complementing these studies, we develop multimodal characterization methods that emphasize secondary electron observables and chemical imaging, linking radiolysis pathways to measured stochastic metrics.

**Presenting Author**

Ricardo Ruiz is a staff scientist at The Molecular Foundry at Lawrence Berkeley National Laboratory. Additionally, he serves as the Director of the Center for High Precision Patterning Science (CHiPPS), a DOE-BES funded Energy Frontier Research Center dedicated to advancing patterning science in the Extreme Ultraviolet lithography era for semiconductor manufacturing. Dr. Ruiz specializes in nanofabrication, lithographic patterning, and self-assembly. From 2006 to 2019, he held various appointments at Hitachi GST/HGST/Western Digital, where he made significant contributions to magnetic bit patterned media and non-volatile memories, and managed a research group focused on block copolymer and nanoparticle lithography. Dr. Ruiz is a fellow of the American Physical Society. He earned his PhD in Physics from Vanderbilt University in 2003 and completed postdoctoral fellowships at Cornell University and IBM T.J. Watson.

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# Discovering EUV Photoresist Chemistry through Automated Reaction Network Construction and Spatiotemporal Kinetic Simulation (Invited)

Samuel M. Blau, Nitesh Kumar, and Frances A. Houle

*Lawrence Berkeley National Laboratory, Berkeley, CA, USA*

EUV lithography drives semiconductor patterning at the nanometer scale, yet the radiolytic chemistry initiated by 92 eV photon absorption in photoresist films remains poorly understood. Unlike thermally activated DUV processes, EUV-driven reactions are initiated by species carrying energy far exceeding typical barrier heights, producing a diverse cascade of radical cations, fragments, and low-energy electrons whose subsequent reactions are difficult to predict from chemical intuition alone. We present a computational workflow that discovers these reaction mechanisms without prescribing them. Starting from an ESCAP photoresist formulation, we use automated reaction network generation to combinatorially construct the space of chemically plausible species and reactions, stochastic pathway sampling to identify the most-trafficked routes, and spatially resolved kinetic simulation to propagate reaction–diffusion kinetics across a 15 nm absorption spur with explicit electron energy tracking. The simulations produce spatiotemporal maps that resolve not only what products form but where and when they form relative to the photoabsorption site, on femtosecond-to-nanosecond timescales. We find that the identity of the initially photoionized species — whether polymer, photoacid generator, or quencher — profoundly shapes the downstream product distribution, governing the balance between productive deprotection and deleterious crosslinking through competing multi-step mechanisms. These results reveal a complex interplay between acid-generating and crosslinking pathways that is inaccessible to conventional mechanistic reasoning, with direct implications for understanding latent image formation in chemically amplified resists.

**Presenting Author**

Dr. Samuel M. Blau is a Research Scientist at Berkeley Lab working at the intersection of computational chemistry, materials science, high-performance computing, and machine learning. He received his B.S. in 2012 from Haverford College and his Ph.D. in Chemical Physics from Harvard University in 2017. Sam has pioneered the use of self-correcting molecular simulation workflows to enable the construction of chemical reaction networks describing complex reaction cascades, e.g. those responsible for battery interphase formation and photoresist patterning. Sam's research group also develops novel datasets, representations, and models for machine learning of chemistry and materials as well as methods that leverage ML model speed and differentiability for accelerated scientific discovery.

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# Supporting Next-Gen EUVL: Hyper-NA and BEUV at CXRO (Invited)

Ryan Miyakawa, Dima Zaytsev, Seno Rekawa, Weilun Chao, Jeff Gamsby, Warren Holcomb, Martin Izquierdo, and Bruno La Fontaine

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The Center for X-ray Optics (CXRO) continues its long-standing role in advancing next-generation extreme ultraviolet lithography by addressing emerging challenges in both Hyper-NA EUV and Beyond EUV (BEUV) regimes. As High-NA EUV enters high-volume manufacturing, new questions arise in resist performance, pattern fidelity, and imaging limits that extend toward both higher numerical apertures and shorter wavelengths.

At the Advanced Light Source, the Berkeley Microfield Exposure Tool (MET5) is being pushed to $k_1 \approx 0.26$ to probe resist resolution limits under scanner-relevant conditions, and is conducting studies supported by the Blue-X TWG such as exposure dose partitioning. In parallel, a new grating-based interference lithography platform, developed in partnership with Brookhaven National Laboratory, enables large-area exposures of dense line and contact patterns to isolate resist and materials effects.

This platform also provides a bridge to BEUV by enabling operation at shorter wavelengths (6.x and 3.x nm) for early-stage materials screening. Planned polarization modules further enable controlled studies of vector imaging effects relevant to Hyper-NA systems. Together, these efforts position CXRO to support both near-term Hyper-NA challenges and longer-term transitions toward next-gen EUVL.

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# Interference Lithography at EUV and Beyond at the XIL-II beamline (Invited)

Iacopo Mochi, Dimitrios Kazazis, Michaela Vockenhuber, David Piguet, and Yasin Ekinci

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The XIL-II beamline of the Swiss Light Source is dedicated to soft X-ray interference lithography and metrology, covering the energy range from 91.8 to 500 eV. The beamline is currently being commissioned following a major upgrade to the synchrotron completed in 2024. The XIL-II beamline will soon feature a new end station designed for EUV and BEUV lithography, with multiple writing modes, including direct writing, grating and mirror-based interference lithography, and holographic lithography. These developments aim to enable the patterning of complex structures and higher resolution, thanks to improved thermal and mechanical stability. In this presentation, we discuss the current status of the upgrade, outline the plan for pilot experiments, and provide a timeline: the first pilot experiments are scheduled to begin in Q3 2024, with initial results expected by the end of the year.

**Presenting Author**

He earned his PhD in 2005, followed by a role at the Arcetri Astrophysical Observatory working on infrared spectroscopy instrumentation. In 2008 he joined the Center for X-Ray Optics at Lawrence Berkeley National Laboratory, where he began his work on extreme ultraviolet (EUV) microscopy and photolithographic mask inspection. After a position at imec focused on EUV photomask SRAFs, he joined the Paul Scherrer Institute in 2016, where he now leads the Advanced Lithography and Metrology group, developing synchrotron-based instrumentation for EUV lithography and soft X-ray metrology.

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# Iodine Functionalized Metal-Organic Cluster EUV Resists for High-Resolution Patterning with Fab-Compatible Processing

Manvendra Chauhan[1], Neha[1], Sachin[1], Ashutosh Joshi[2], Meghana Sharma[2], Abhimanew Dhir[2], Bhaskar Mondal[2], Ranbir Singh[3], Robin Khosla[1], Satinder K. Sharma[1], and Ralph Dammel[4]

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Pushing extreme ultraviolet lithography (EUVL) toward high-resolution patterning at nodes down to 10 nm or below is strongly influenced by stochastic effects in the resist, which manifest as line-edge roughness (LER) and pattern collapse. In this study, a metal-organic cluster (MOC)-based resist system is developed using high-EUV absorption-centred clusters coordinated with iodine-functionalized ligands enabling enhanced EUV photon absorption and efficient secondary electron generation, thereby improving the utilization of deposited energy during exposure. The developed resist formulations were first examined using electron beam lithography (EBL) to establish exposure and response behaviour prior to EUV implementation. A clear shift toward lower dose-to-size was observed for iodine-containing formulations, accompanied by improved feature definition. Line/space patterns below 10 nm were resolved with comparatively lower edge roughness, which is attributed to more localized energy deposition and reduced long-range chemical effects. In addition, the inorganic content of the cluster framework enhances mechanical stability, reducing deformation during development. The results indicate that iodine-functionalized MOC resists can address key limitations associated with stochastic variability while maintaining pattern integrity, making them relevant candidates for future EUV patterning schemes.

**Presenting Author**

Prof. Satinder Kumar Sharma, Ph.D. (SMIEEE, IETE Fellow, SPIE Member), is a full professor in the School of Computing and Electrical Engineering at IIT Mandi. He earned his PhD in Electronic Science from Kurukshetra University, India, in 2007 & completed a postdoctoral fellowship at IIT Kanpur, India (2007-2010). He later joined IIIT-Allahabad, India in 2011 before moving to IIT Mandi in 2012, where he became a full professor in 2021. Prof. Sharma has raised over INR 4,000 lakhs in research funding from agencies such as MeitY, DST, ISRO, and international bodies such as DAAD and Semiconductor Research Corporation. He has collaborated with institutions such as IITs, Lawrence Berkeley National Laboratory (USA), and Stuttgart University (Germany). He has published over 140 peer-reviewed articles in reputed international journals and presented more than 100 invited talks and research papers at national and international conferences. His current research interests include microelectronic circuits and systems, CMOS devices, nonvolatile memories, nano/microfabrication, advanced lithography techniques, sensor design, and self-assembly technologies. His research interests span microelectronics, CMOS devices, MEMS/NEMS, advanced lithography, sensors, photovoltaics, and self-assembly.

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# Molecular Layer Deposition of Metal Coordination Polymer Resists for EUV Lithography (Invited)

L. Viet Than[1], M. Kim[2], O. Kostko[3], B. Shong[2], and Stacey F. Bent[1]

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Inorganic resists are promising for EUV lithography because compared to traditional organic resists, they have higher etch resistance, are more impervious to pattern collapse, and are more absorbing of EUV radiation. Molecular layer deposited (MLD) metal-organic photoresists offer intrinsic advantages in precise thickness control and chemical homogeneity. However, many MLD resists have poor EUV and electron beam sensitivity, leading to the need to explore new molecular designs. We introduce MLD resists in which we tune the organic linker to develop an efficient solubility switch mechanism. Promising results are found with MLD-grown aluminum oxalate thin films. We apply surface spectroscopies to probe the chemical structure, and we investigate the resist patterning via electron beam lithography and flood EUV exposure. Results show that the metal oxalate films are negative tone resists and that applying a post-exposure bake can improve sensitivity without sacrificing pattern quality. Using electron beam lithography, line/space patterns as small as 12 nm half pitch are resolvable, with a line width roughness (LWR) of 3.3 nm. This work introduces a new chemical design applicable to hybrid MLD photoresists and highlights the importance of the organic ligand in determining the efficiency of the patterning mechanism.

**Presenting Author**

Stacey F. Bent is Jagdeep and Roshni Singh Professor at Stanford University, where she is Professor of Chemical Engineering and of Energy Science and Engineering, and Professor by courtesy of Chemistry, Materials Science and Engineering, and Electrical Engineering. Her research focuses on understanding surface chemistry, materials synthesis, and atomic layer deposition, and applying this knowledge to problems in sustainable energy, microelectronics, and advanced manufacturing. Bent was elected to the U.S. National Academy of Engineering in 2020. She is also a Fellow of the American Chemical Society (ACS) and the American Vacuum Society (AVS) and has received various awards for her contributions to surface chemistry, materials engineering and ALD innovation.

P54

# Holistic Integration of Novel Patterning Technologies for High-NA EUV Lithography (Invited)

Cong Que Dinh

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Both CAR and MOR approaches encounter critical challenges when transitioning to high-NA EUV, including strict requirements on resolution, line edge roughness, sensitivity, and defectivity. This work presents a pathway toward overcoming present limitations and accelerating next-generation device fabrication.

**Presenting Author**

Dr. Dinh is currently an expat in TEL Technology Center, America, LLC in Albany, New York. Before this position, he was a lithography senior specialist at Advanced Technology Department in Tokyo Electron Kyushu, where he was working on development of track processes for next generation lithography. Prior joining TEL, he was at Osaka University where he focused on EUV resists and advanced lithography. He obtained his Erasmus Mundus joint master’s degree in Photonics from Ghent University, Free University of Brussels, University of St Andrews and Herriot-Watt University. He accomplished his PhD in Osaka University in 2016.

P55

# Development of Resist Materials under JST K Program (Invited)

Takahiro Kozawa[1], Yuko Tsutsui Ito[1], Kohei Machida[2], and Tomoyuki Enomoto[2]

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The 13.5 nm extreme ultraviolet (EUV) exposure tool with hyper numerical aperture (0.75 NA) and short wavelength EUV (BEUV) exposure tool have been under investigation to advance the nanofabrication technology for manufacturing the semiconductor devices. These next generation lithographies require highly resolving resist materials. However, the current standard resist, called a chemically amplified resist, utilizes the acid catalytic reaction for the solubility change of resist polymer. The acid diffusion limits the special resolution of resist materials, although the sensitivity is significantly improved. Under such a background, the development of high-resolution resists with a highly absorptive element for EUV photons has attracted much attention for next-generation lithographic applications. In this study, we investigated the polarity-change copolymer resists comprising EUV absorption unit and polarity-change unit. Their lithographic performances are preliminary evaluated using a 125 keV EB writer. The reaction mechanism and lithographic performance will be reported.

**Presenting Author**

Takahiro Kozawa is a professor of SANKEN, the University of Osaka. He earned his BS and MS degrees in nuclear engineering from the University of Tokyo, and Ph. D. degree in chemical engineering from Osaka University in 1990, 1992, and 2003, respectively. His work is mainly focused on beam-material interaction and beam-induced reactions in resist materials.

P56

# Design of Block Copolymers for Directed Self-Assembly to Mitigate Stochastic Challenges in EUV Lithography (Invited)

Kyunghyeon Lee

*Pritzker School of Molecular Engineering (PME), University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA*

Directed self-assembly (DSA) of block copolymers (BCPs) has been proven to be a robust and complementary patterning strategy for extreme ultraviolet (EUV) lithography. In this "EUV + DSA" strategy, EUV resist patterns are first converted into chemical pre-patterns. BCPs are then assembled on these templates, forming well-defined nanodomains that follow the underlying chemical templates. By selectively removing one block, the DSA patterns are transformed into topographic etch masks for pattern transfer into device-relevant inorganic materials. By leveraging the thermodynamically driven BCP nanostructures, EUV + DSA successfully rectify the stochastic defects and rough pattern edges in EUV patterns, commonly referred to as "pattern rectification". This effectively relaxes the stringent requirements for EUV resists to simultaneously meet high resolution, low roughness, and high sensitivity, which in turn reduces overall energy costs. Manufacturing-scale studies by IMEC and Intel have demonstrated that this process can achieve line width roughness (LWR) below 2 nm with the low-quality resists at 50% reduced EUV doses, meeting critical industry requirements.

Here, we address the fundamental materials parameters that govern the pattern quality in EUV + DSA. Critical design parameters are governed by the thermodynamic quantities, namely the Flory–Huggins interaction parameter ($\chi$), the segregation strength ($\chi N$), and the surface energy ($\gamma$), all coupled to the block chemistry. $\chi$ and $\chi N$ determine the lamellar domain spacing (resolution) and interfacial width (line roughness), while $\gamma$ governs perpendicular domain orientation throughout the film. A-block-(B-random-C) architectures are employed to decouple these covarying parameters, enabling independent tuning of resolution, perpendicular orientation, interfacial sharpness, and pattern transfer capability. By integrating EUV-derived chemical pre-patterns, top-down SEM/PSD analysis, and X-ray scattering methods, we establish a direct framework linking molecular design, interfacial width, and lithographic performance.

**Presenting Author**

Kyunghyeon Lee is a postdoctoral researcher at the Pritzker School of Molecular Engineering (PME), University of Chicago, under the supervision of Prof. Paul Nealey. His research focuses on the directed self-assembly (DSA) of block copolymers and its integration with extreme ultraviolet (EUV) lithography for high-precision, energy-efficient semiconductor manufacturing. He develops materials and nanofabrication strategies for "EUV + DSA" and investigates nanoscale interfacial structures in block copolymers to improve pattern roughness. He received his Ph.D. in Chemistry from Seoul National University in Korea, where he studied colloidal assemblies of block copolymer micelles.

P57

# Dry Developing Process of Molecular-Atomic-Layer-Deposited Hybrid Dry Photoresist for EUV Lithography

Thi Thu Huong Chu[1], Dan N. Le[1], Minjong Lee[1], Nikhil Tiwale[2], Chang-Yong Nam[2], and Jiyoung Kim[1]

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EUVL is the key enabling technology for sub-10 nm metal half-pitch nodes.1 However, one of the primary bottlenecks lies in the development step of photoresists. Conventional wet development frequently induces pattern collapse due to wet process capillary forces.2,3 Additionally, solvent–resist interactions introduce variability that degrades line-edge roughness (LER) and increases stochastic defects, both of which are detrimental to device yield.

To address these challenges, dry development processes are emerging as a promising alternative, eliminating the patterning issues related to wet developers as well as their associated environmental cost. Here, we present a dry development approach of the Zn-based hybrid inorganic–organic resist systems deposited by molecular atomic layer deposition (MALD). The resist films were patterned using low-energy electron beam lithography (0.1 kV EBL) to mimic EUV photon exposure. Dry development was then carried out through chemical vapor exposure of hexafluoroacetylacetone (hfacH), which reacts with the Zn-based resists, generating volatile products such as Zn(hfac)2 along with organic by-products. We will discuss detailed results in this presentation.

By combining MALD-based hybrid resist materials with vapor-phase development, this approach not only mitigates fundamental limitations of wet processing but also opens pathways for scalable, high performance patterning required for next-generation semiconductor manufacturing.

This work is supported by the U.S. DOE Office of Science Accelerate Initiative Award 2023- BNL-NC033-Fund.

[1] I. Giannopoulos et al., Nanoscale, 2024, 16, 15533–15543.
[2] T. S. Kulmala et al., Proc. SPIE, 2016, 9776, 97762N.
[3] N. Kenane et al., J. Photopolym. Sci. Technol., 2024, 37, 257–262.

**Presenting Author**

Jiyoung Kim is a professor of Materials Science and Engineering and affiliated at Depts. of Electrical and Mechanical Engineering at the University of Texas at Dallas since 2005. He received the B.S. (1986) and the M.S. (1988) at Seoul National University, and the Ph.D. (1994) at the University of Texas at Austin. He worked as an integration engineer at Texas Instrument, Inc (Dallas, TX) from 1994 to 1996. From 1996 to 2005 he was an assistant/associate professor at Kookmin University, (Seoul, Korea). His research interests are in the area of future semiconductor process integration technology, particularly on ALDs including EUV dry PR materials and process development. development of inorganic molecular resists for EUV, Blue-X (6.7 nm) and Blue-X (3.1 nm) Lithography.

P71

# Broadband EUV Imaging Spectrometry

Mats Brinkman

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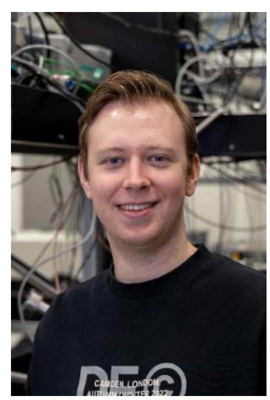
The advancement of EUV source technology relies not only on improving laser produced plasma (LPP) performance but also on developing diagnostic tools capable of accurately quantifying these improvements. Spatially resolved plasma emission has been well characterized in the past, using multilayered mirrors at 13.5 nm wavelengths. However, retrieval of broadband spectrally resolved spatially emission profiles is not possible using this method. In this work, we introduce a deconvolution-based method that enables the reconstruction of spectrally resolved spatial emission profiles from a broadband EUV imaging spectrometer employing dispersion-matched tapered zone plates. Using point spread functions derived from Rayleigh-Sommerfeld angular spectrum propagation modeling, we reconstruct emission profiles of tin-based LPPs. Our results demonstrate accurate plasma size reconstruction down to the diffraction limit, marking a significant improvement over earlier empirical fitting-based approaches and revealing clear differences in inferred source brightness. This work paves the way to adopt the concept of the broadband imaging spectrometer to diagnose plasma in academic and industrial settings. We will put the work in context of the full suite of ARCNL diagnostics.

**Presenting Author**



Mats Brinkman received his BSc degree from the Eindhoven University of Technology and his MSc from Leiden University. He is currently a PhD student studying EUV plasma processes at ARCNL and the University of Twente, under the supervision of Prof.dr. Versolato, dr. Bayraktar and Prof.dr. Ackermann. His research focuses on the research on 2-um LPP-sources and developing diagnostics to accurately characterize those and other plasma.

P72

# EQS-10: A Next-Generation DPP EUV Light Source (Invited)

David Reisman[1], Nick Lubinsky[1], Daniel Arcaro[1], Kosuke Saito[2], Wolfram Neff[1], Aaron Feldman[1], Mike Roderick[1], Mike Kozlowski[1], and Don McDaniel[1]

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*[2]Hamamatsu Photonics K.K., Japan*

Energetiq Technology's EQS-10 Electrodeless Z-Pinch™ EUV light source uses a xenon plasma Z-pinch to produce 13.5 nm (±1% BW) radiation with an EUV power of ~40W. Key technologies in this next-generation source design include high-voltage switching, Xe direct fueling, and pre-ionization. Using these features, we show how the system can be optimized for high-brightness and high-NA light collection. Specifically, we use radiation-MHD code calculations to explore the development the source and obtain highly optimized designs. Experimental data and their comparison to simulation results will be presented.

**Presenting Author**

David Reisman is a Principal Scientist at Energetiq Technology, focusing on the development of EUV Z-pinch systems. David received his Ph.D. in physics at the University of California, Davis. Before joining Energetiq, David worked at Lawrence Livermore and Sandia National Laboratories in high-energy-density physics (HEDP).

P73

# Development of Sn-LPP EUV Light Source for Actinic Mask Inspection

Tomoyoshi Toida, Takashi Suganuma, Shinji Nagai, Fumio Iwamoto, Kenichi Miyao, Hideyuki Hayashi, Takuya Ishii, Yoshifumi Ueno, Tamotsu Abe, and Hiroaki Nakarai

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EUV lithography has been adopted worldwide for high-volume manufacturing. Actinic EUV mask inspection tools have become essential for detecting mask defects that are printable to the wafer. EUV light sources used in these tools are required to deliver high brightness, high availability, and high reliability.

Gigaphoton has developed a Sn-LPP EUV light source for actinic mask inspection, including a droplet generator, main/pre-pulse lasers, and debris mitigation using $H_2$ background gas. We achieved a brightness of 120 W/mm$^2$·sr at the plasma point during a 5500-hour test with the system operated at a repetition rate of 20 kHz. The 3σ EUV energy stability was approximately 5%, and the system availability reached 99%. The reflectivity degradation of the EUV collector mirror was limited to 11%. These results demonstrate the potential for one-year maintenance-free operation of the EUV light source, and the system is scalable to higher brightness by increasing the repetition rate.

We are developing a 40 kHz system with a higher repetition rate laser and have achieved more than 240 W/mm$^2$·sr at the plasma point. Long-term continuous operation is currently ongoing. We present the progress of our EUV light source.

**Presenting Author**

Tomoyoshi Toida joined the Advanced Light Source Development Department at Gigaphoton in 2017. His research focuses on improving conversion efficiency to in-band EUV and optimizing gas flow for tin debris mitigation.

P74

# EUV Exposure for Photo-Chemical Materials and LPP-EUV Source Research for Semiconductor Manufacturing II (Invited)

Hakaru Mizoguchi[1,2], Kentaro Tomita[3], Daisuka Nakamura[1], Yukihiro Yamagata[4], Takeshi Higashiguchi[6], Atsushi Sunahara[5], Katsunobu Nishihara[7], Takashi Toshima[2], Hiroki Kondo[1,2], Takuji Sakamoto[2], Tanemasa Asano[2], and Masaharu Shiratani[1,2]

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*[5]Center for Materials Under eXtreme Environment (CMUXE), School of Nuclear Engineering, Purdue University, 500 Central Drive, West Lafayette, IN 47907, USA*
*[6]Utsunomiya University, Mine-machi 350, Utsunomiya-shi 321-8585, Tochigi, Japan*
*[7]Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, Osaka 565-0871, Japan*

In this paper, we will report about new EUV research activities in Kyushu-Univ. in Japan[1)].
(1) EUV Photon
Concept of EUV exposure and material analysis for material industry is reported. We already established private company "EUV Photon" in July 2024. EUV Photon are supporting EUV material industry, by using EUV Irradiation apparatus (Fig.1), evaluation from material science with leading edge measurement technology with corroboration of Kyushu-Univ. We start new "EUV Irradiation Center" in Fukuoka from this April.
(2) K-Program by MEXT
K-program "Next-Generation Semiconductor Process Technology do EUV and BEUV " has started in Japan. Kyushu-university group has joined this program as evaluation of new driver laser produced plasma and new EUV mirror which will be developed in this program. Our group is consist of "EUV plasma creation" sub-group in Kyushu-University, plasma measurement sub-group in Hokkaido Univ. and plasma simulation

sub-group in Osaka Univ.. Latest Thomson Scattering Measurement and simulation expect high EUV creation efficiency more than 10%. We are preparing a new plan of S-MET chamber (Fig.2) for demonstration of high efficiency EUV source of K-Program in Japan. We will report latest status of this program.

At the conference, we will report latest research plan for challenging higher power EUV source.

[1] Hakaru Mizoguchi, Kentaro Tomita, Daisuke Nakamura, Yukihiro Yamagata, Takeshi Higashiguchi, Atsushi Sunahara, Katsunobu Nishihara, Takashi Toshi-ma, Hiroki Kondo, Takuji Sakamoto, Tanemasa Asano and Masaharu Shira-tani: " Plasma Dynamics and Future of LPP-EUV Source for Semiconductor Manufacturing II" SPIE 13215-63 (2024) .

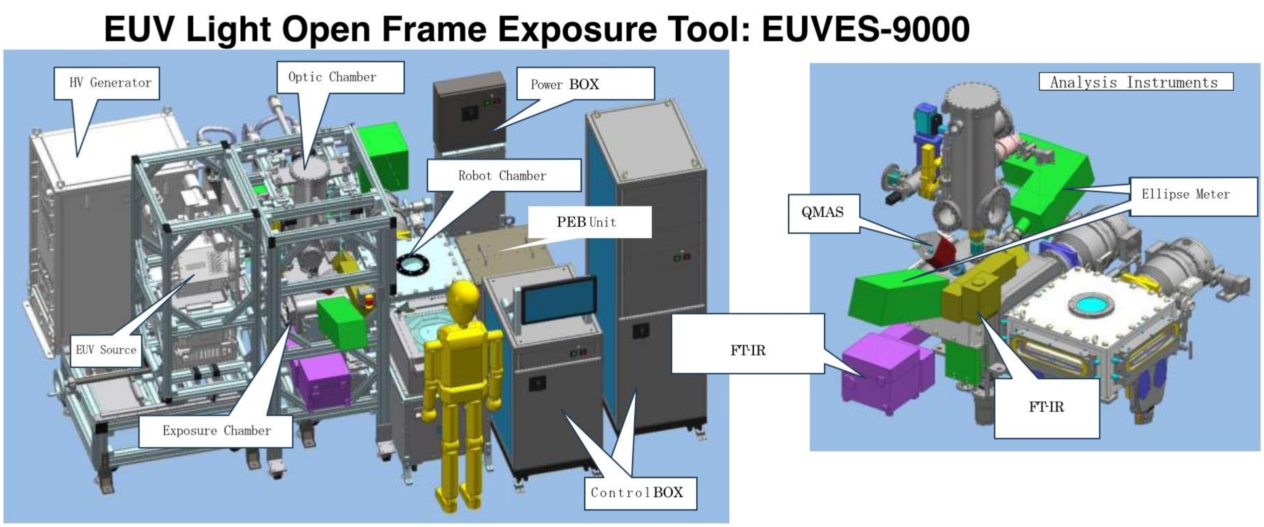


Fig.1 DPP EUV Light Source and Exposure Tool EUVES-9000* (*Produced by Litho Tech Japan)

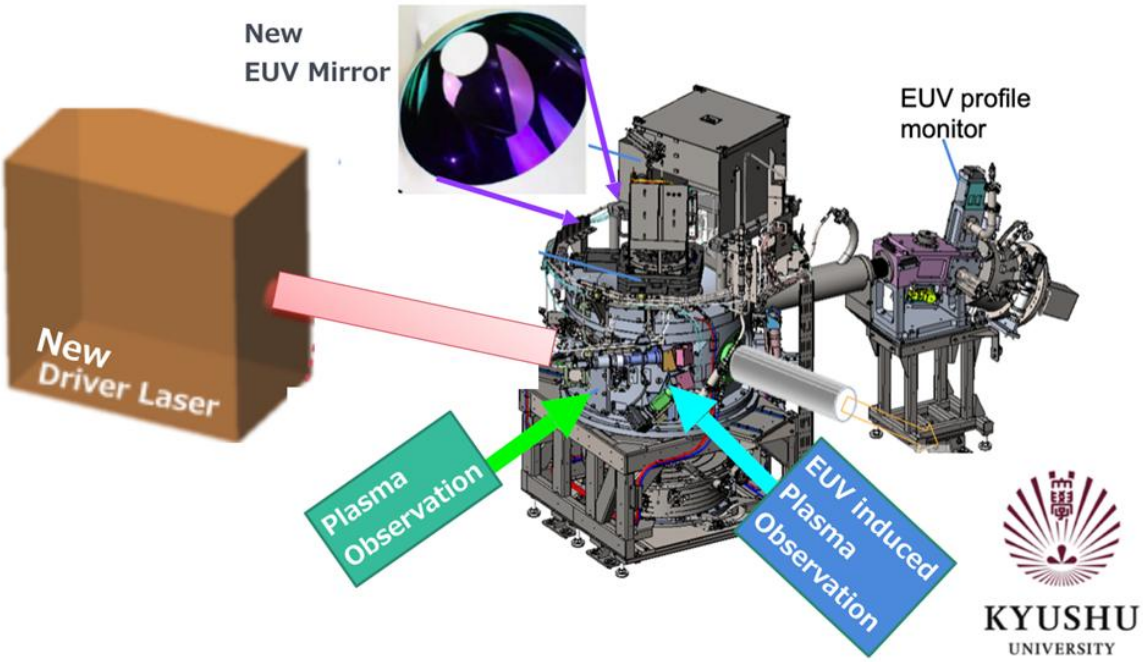


Fig.2 Smart Laser and Mirror Evaluation Tool by Kyushu University in K-Program

**Presenting Author**

Hakaru Mizoguchi is a Guest Professor of Kyushu University. ( He was Senior Fellow of Gigaphoton Inc.) He is Fellow of The International Society of Optical Engineering (SPIE), and member of The Laser Society of Japan and The Japan Society of Applied Physics.He received a diplomat degree in plasma diagnostics field from the Kyushu university, Fukuoka, Japan in 1982 and join Komatsu ltd.. He joined CO2 laser development program in Komatsu for 6 years. After that he was guest scientist of Max-Plank Institute Bio-Physikalish-Chemie in Goettingen in Germany 2 years, from 1988 to 1990. Since 1990 he concentrated on KrF, ArF excimer laser and F2 laser research and development for lithography application. He was general manager of research division in Komatsu Ltd. until 1999. He got Dr. degree in high power excimer laser field from Kyushu university in 1994. In 2000 Gigaphoton Inc. was founded. He was one of the founders of Gigaphoton Inc.. From 2002 to 2010 he organized EUV research group in EUVA program. Now he is promoting EUV light source development.

P75

# Scaling of EUV Conversion Efficiency with Material and Laser Intensity in High-Z Plasmas

Tirtha R. Joshi

*Center for Energy Research, University of California San Diego, La Jolla, CA, USA*

There is strong interest in plasma sources emitting below 13.5 nm for next-generation semiconductor lithography. Gadolinium (Gd) and bismuth (Bi) laser-produced plasmas are promising beyond-extreme-ultraviolet (BEUV) sources. This study identifies optimal plasma conditions for BEUV generation and examines the influence of laser intensity on emission and conversion efficiency. Tin (Sn) plasmas at 13.5 nm are included as a reference EUV source. Radiation-hydrodynamic simulations were performed using FLASH and post-processed with SPECT3D for laser intensities of ~1011-1012 W/cm2, using a 1064 nm, 10 ns Gaussian pulse with a 100 µm focal spot. EOS and opacity inputs were generated under LTE with continuum lowering. Sn plasmas produced strong 13.5 nm emission at 2.4 x1011 W/cm2 from Sn8+−Sn14+ (plasma temperature of ~ 20-40 eV), while higher intensities increased ionization but reduced efficiency. Gd plasmas generated strong 6.7 nm emission at (3–6) x1011 W/cm2 from Gd12+- Gd25+ (plasma temperature of ~50-90 eV), with improved efficiency at higher intensities. Bi plasmas required higher intensities, producing 3.5-5 nm emission from Bi25+-Bi46+ at (0.6–4) x1012 W/cm2 (plasma temperature of ~120-200 eV). Post-processing of the hydrodynamic simulations identified spatial regions just beyond the critical surface where EUV/BEUV emission is most efficient for Gd, Bi, and Sn plasmas. LTE overestimated emission, while optically thin NLTE underestimated it, emphasizing the need for accurate collisional-radiative modeling.

This research is based upon work supported by the U.S. Department of Energy, Office of Science/Office of Fusion Energy Sciences, as part of the Accelerating Next Generation EUV Lithography (ANGEL) project under Extreme Lithography & Materials Innovation Center (ELMIC), a Microelectronics Science Research Center (MSRC).

**Presenting Author**

Tirtha Joshi is an Associate Project Scientist at the Center for Energy Research, University of California, San Diego. He earned his Ph.D. in Physics from the University of Nevada, Reno, and previously worked at the Laboratory for Laser Energetics and Los Alamos National Laboratory. His research focuses on inertial confinement fusion, radiation-hydrodynamics simulations, X-ray spectroscopy, and next-generation EUV lithography using laser-produced plasmas.

P77

# Control of the Ion Energy Distribution Function in Double-Pulse Laser-Produced EUV Plasmas (Invited)

Kentaro Tomita[1], Atsushi Sunahara[2], Akira Sasaki[2,3], and Katsunobu Nishihara[2]

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*[3]Institute for Quantum Science and Technology, 8-1-7 Umemidai, Kizugawa-shi, Kyoto, 619-0215 Japan*

Mitigation of high-energy ions is crucial for laser-produced plasma (LPP) extreme ultraviolet (EUV) light sources, as energetic ions cause severe damage to collector mirrors. However, the ion energy distribution function (IEDF) is fundamentally governed by plasma parameters such as electron temperature ($T_e$) and density ($n_e$). Therefore, reducing ion energies while maintaining strong EUV emission requires plasma manipulation based on the plasma parameters.

Double-pulse (DP) laser irradiation scheme, consisting of a pre-pulse followed by a main pulse, has been reported as an effective method for ion energy reduction, regardless of target geometry [1,2]. Nevertheless, the underlying physical mechanisms remain insufficiently understood.

In this study, Sn plasmas were generated using two 1064 nm wavelength, 8 ns pulse Nd:YAG lasers irradiating a planar target. Collective Thomson scattering diagnostics were performed to characterize $n_e$ and flow velocity in the pre-plasma formed by the pre-pulse and the main-plasma produced by the main-pulse.

The results show that the IEDF strongly depends on pre-plasma density and expansion dynamics. Ion energy reduction is attributed to shielding of the ion-acceleration electric field and the formation of a two-fluid plasma structure during expansion. These findings provide a physics-based framework for ion energy control in advanced EUV light sources.

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This work was supported by JST K Program Grant Number JPMJKP24M1 Japan.

**Presenting Author**

He received B. S., M. S., and Ph. D. degrees from Kyushu University, Japan, in 2002, 2004, and 2014, respectively. In November 2006 he was appointed Research associate at Kyushu University and became Assistant Professor in April 2007 at the same university. He became Associate professor in July 2020 at Hokkaido University, Japan.

P78

# Accelerating Next-Generation EUV Lithography (ANGEL) through a Co-Design of Laser-Produced Plasma Sources and Multilayer Mirrors (Invited)

Arun Devaraj[1], Sivanandan S. Harilal[1], Semanti Mukhopadhyay[1], Ajay Karakoti[1], Tiffany Kaspar[1], Maxim Ziatdinov[1], Bruno La Fontaine[2], Farhat N. Beg[3], Peter J. Bruggeman[4], Gennady Miloshevsky[5], and Igor Golovkin[6]

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*[5]Virginia Commonwealth University, Richmond, VA, USA*
*[6]Prism Computational Sciences, Inc, 455 Science Dr. Suite 140, Madison, WI 53719, USA*

Extreme ultraviolet lithography (EUVL) is central to continued feature scaling in microelectronics manufacturing. EUVL performance depends on laser-produced plasma (LPP) sources that generate 13.5 nm radiation from laser-driven tin droplets and on multilayer mirrors (MLMs) that transport this light to the wafer. Key barriers to high-volume manufacturing include improving LPP conversion efficiency and limiting MLM degradation caused by tin debris/ion irradiation and secondary hydrogen plasma. The ANGEL project, supported by the U.S. Department of Energy Microelectronics Science Research Center, investigates EUV photon generation, radiation transport in LPP sources, and the mechanisms governing MLM damage under realistic operating conditions. The work combines operando plasma diagnostics with collisional-radiative modeling to quantify tin ion kinetics and radiative transfer, while machine-learning-guided experimental design accelerates optimization of source efficiency. Multiscale and materials degradation experiments and modeling are used to connect plasma conditions to mirror performance and guide improved MLM materials. Outcomes are expected to enable higher-power, more efficient EUV sources and more durable optics, lowering EUVL cost of ownership and strengthening U.S. manufacturing competitiveness.

**Presenting Author**

Arun Devaraj is a chief scientist in the Physical and Computational Sciences Directorate at Pacific Northwest National Laboratory. He is a co-director of the ANGEL project funded by the DOE Office of Science as part of the microelectronic science research centers and he leads the multi-layer mirror degradation thrust 2. Throughout his 19-year research career, Dr. Devaraj has focused on understanding atomic-scale transformations in materials both during synthesis and degradation in extreme environments. He employs cutting-edge techniques, including advanced electron microscopy, atom probe tomography, and synchrotron-based X-ray diffraction. He was awarded a DOE Basic Energy Sciences early career research award in 2020.

P79

# Pulse Conditioning and Material Comparisons for Optimized EUV and Beyond-EUV Emission from Laser-Produced Plasmas

Owen Bardeen[1], Tirtha Joshi[1], Alamgir Mondal[1], Igor Golovkin[2], S. Harilal[3], and Farhat Beg[1, 4]

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*[3]Pacific Northwest National Laboratory, Richland, WA, USA*
*[4]Mechanical and Aerospace Engineering, University of California San Diego, La Jolla, CA, USA*

Efficient generation of extreme ultraviolet (EUV) and beyond-EUV (B-EUV) radiation from laser-produced plasmas is critical for next-generation lithography and laboratory light sources. Pulse conditioning strategies enhance EUV emission from tin (Sn) by tailoring density gradients and absorption, yet systematic studies across alternative high-Z materials remain limited. Gadolinium (Gd) plasmas exhibit strong emission near 6.7 nm, highlighting their potential for B-EUV sources [1]. We propose experiments to map the effects of main-pulse intensity delay on plasma evolution and short-wavelength emission from Sn, Gd, Scandium (Sc), and Bismuth (Bi) foils. A 12 ns pulse will generate controlled plasmas with energies scanned up to 25 J to identify optimal conditioning for each material and optimize EUV/B-EUV output. Plasma expansion and density profiles will be diagnosed using interferometry and shadowgraphy, while emission is measured with a calibrated XUV spectrometer and fast diodes to quantify spectral brightness, conversion efficiency, and charge-state distributions. Radiation-hydrodynamic simulations with FLASH [2] will model pre-plasma formation and expansion, and Spect3D [3] will link measured spectra to plasma temperature, density, and ionization balance. Correlating pulse conditions with plasma dynamics and emission will establish material-dependent scaling laws for optimized short-wavelength sources and provide benchmarks for laser-plasma modeling.

This research is based upon work supported by the U.S. Department of Energy, Office of Science/Office of Fusion Energy Sciences, as part of the Accelerating Next Generation EUV Lithography (ANGEL) project under Extreme Lithography & Materials Innovation Center (ELMIC), a Microelectronics Science Research Center (MSRC).

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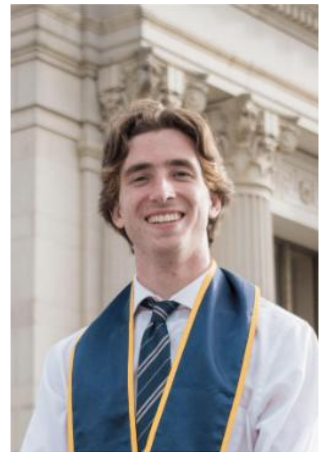
[3] Prism Computational Sciences, Inc., "Spect3D: Collisional-radiative spectral analysis code," Prism Computational Sciences Software Documentation, 2023.

**Presenting Author**



Owen Bardeen is a lover of high energy density physics and laser science, a passion discovered during his undergraduate degree in physics at UC Berkeley. After working with the Rocca lab at CSU and the source team at ASML San Diego during this time, he became enamored by EUV technology, and joined the Beg lab at UCSD to pursue his PhD in Mechanical Engineering and explore EUV further. His research involves simulation work of EUV-emitting Tin plasmas, in collaboration with ASML, and studying beyond-EUV sources, doing experiments in the UCSD facility supplemented with FLASH and PRISM software simulations.

P80

# Comparative Collective Thomson Scattering Study of Single and Dual-Trigger LDP Tin Plasmas in an EUV Source (Invited)

Hideyuki Sera[1,2], Akihisa Nagano[1], and Kentaro Tomita[2]

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We report a diagnostic comparison of single-trigger and dual-trigger laser-assisted discharge tin plasma (LDP) EUV sources using collective Thomson scattering (CTS) system. In tin-plasma EUV sources, the EUV in-band (2% BW) emission is governed primarily by electron temperature and electron density. Dual-trigger operation has been reported in prior EUV-source literature and is widely described as a practical approach to increase source brightness and output power by tailoring the preconditioning and subsequent Z-pinch dynamics of the discharge plasma. However, direct experimental comparisons of the underlying plasma parameters under identical diagnostics remain limited. We have extended our CTS analysis pipeline to retrieve electron temperature, electron density, and bulk flow velocity. Under the same configuration, we determined the plasma conditions at the timing when the EUV energy monitor signal reaches its maximum. For the single-trigger configuration, we obtained $T_e$ = 21 eV and $n_e$ = 7×10^24 $m^{-3}$. For the dual-trigger configuration, we obtained $T_e$ = 23 eV and $n_e$ = 1×10^25 $m^{-3}$. In addition to these differences in peak-emission conditions, the pinch contraction speed is reduced in the dual-trigger case compared with the single-trigger case. These CTS results provide a quantitative experimental basis to discuss how the second trigger laser modifies the temporal evolution of the LDP, the formation of the high-emissivity state, and the pinch dynamics relevant to EUV source optimization.

**Presenting Author**

Hideyuki Sera is a Chief Engineer at Ushio Inc. He joined the company in 2015 after completing his master’s degree in physics at Keio University. He has been involved in laser-based measurement systems and has served as the laser module owner for EUV light sources. Currently, he works as an R&D scientist focusing on EUV light source development. He is also currently enrolled in a Ph.D. program at Hokkaido University, where he conducts research on collective Thomson scattering diagnostics of laser-assisted discharge plasma EUV light sources and on performance improvements of LDP source.

P82

# Effective Temperature Approximations for Use in Modeling Non-LTE Tin Plasmas (Invited)

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Atomic populations in non-local thermodynamic equilibrium (non-LTE) plasmas often follow Boltzmann distributions at temperatures different from the true electron temperature. These non-LTE conditions arise from lower electron densities in the laser-produced plasma, and also can emerge through non-Maxwellian electron distributions in such systems. We study the emergence of so-called effective temperatures in open-N shell tin ions created in laser-produced plasma conditions of relevance for nanolithography. Configuration-average populations are calculated using the Los Alamos suite of atomic structure and population kinetics codes. We have identified the collisional-radiative processes that dominate population flow for hundreds of configurations in relevant ions of tin. The calculations reveal that a single effective temperature can accurately describe the population distributions in the studied conditions. We discuss the origins of this phenomena and show that a simple two-level model can reliably predict the effective temperatures derived from the collisional-radiative calculations. We finally show some comparisons of how these effective temperatures can be used to construct opacity tables for use in rad-hydro modeling of tin plasmas.

LA-UR-20-23016

P83

# Quantum Effects in the Absorption of Laser Light by EUV-Source Relevant Plasmas

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Radiation-hydrodynamics models of the EUV emission from Sn targets illuminated by lasers require the laser absorption rate to be enhanced above theoretical expectations (in order to better match experimental observables). The reason for this enhancement is currently unknown. We explore and quantify enhancements that are predicted by accurate quantum models of the collisional absorption process [1]. Approximate ways of including these effects in radiation-hydrodynamics codes will be discussed.

[1] W.J. Karzas and R. Latter, Electron Radiative Transitions in a Coulomb Field, Astro. J. Supp., Vol 6, p 167 (1961).

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**Presenting Author**

M. Sherlock obtained his PhD in ion kinetic effects in z-pinch plasmas from Imperial College in 2004. He subsequently went on to hold staff positions at the Rutherford Appleton Laboratory (UK) and Lawrence Livermore National Laboratory. His research areas include kinetic model development for laser-plasmas.

P84

# Simulating Fast Ion Debris for Next-Generation Light Sources for Nanolithography (Invited)

Kirill Lezhnin

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Laser-produced plasma from the interaction of a laser with a molten tin droplet is the conventional approach for generating EUV light in lithography scanners. Scaling to higher source power and shorter exposure wavelengths is currently being pursued to improve scanner throughput and enable smaller feature sizes. Two active research directions for future source development are the use of solid-state laser drivers for tin plasmas, and the exploration of alternative target materials for shorter wavelength emission. In both cases, optimizing EUV output must be balanced against debris mitigation to enable high-volume manufacturing. In this work, we use radiation hydrodynamics and collisional particle-in-cell simulations[1] to study laser-driven ion debris generation for a range of target materials and laser parameters. We examine how laser wavelength and target material affect the production of fast ion debris and assess how reliably radiation hydrodynamics simulations can predict ion debris spectra.

[1] S. R. Totorica, K. Lezhnin, D. J. Hemminga, J. Gonzalez, J. Sheil, A. Diallo, A. Hyder, W. Fox, APL (2024)

**Presenting Author**

Kirill Lezhnin is a postdoctoral researcher at the Princeton Plasma Physics Laboratory, working on kinetic and radiation hydrodynamic simulations of laser-plasma interactions in high-energy-density plasmas and EUV light sources. He received a PhD from Princeton University in 2022. His graduate work focused on kinetic simulations of laser-driven secondary sources and laboratory astrophysics experiments.

P85

# Atomic Data and Collisional-Radiative Atomic Kinetics Simulations for EUV/x-ray Sources (Invited)

Igor Golovkin and Ming Gu

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Prism Computational Sciences, Inc. uses state-of-the-art plasma radiation and atomic physics simulation tools for investigating radiation sources at short wavelengths for next-generation lithography systems. A suite of well-benchmarked radiation-hydrodynamics[1], atomic kinetics, and spectral analysis[2] codes can simulate the characteristics of radiation emitted from laser-produced plasmas. Prism's atomic and radiation physics simulation tools have been previously applied to the analysis of EUVL LPP experiments and have been shown to accurately predict the properties of plasmas for 13.5 nm radiation sources. These properties include not only time-integrated conversion efficiencies, but also time- and spectrally-resolved radiation. We will discuss key physics aspects of the simulations and present new results for the radiation sources in water window, including line and UTA emitters. We will highlight the importance of accuracy and completeness of atomic structure calculations and address possible effects of non-equilibrium atomic kinetics and non-local radiation transport.

This research is based upon work supported by the U.S. Department of Energy, Office of Science/Office of Fusion Energy Sciences, as part of the Accelerating Next Generation EUV Lithography (ANGEL) project under Extreme Lithography & Materials Innovation Center (ELMIC), a Microelectronics Science Research Center (MSRC).

[1] *HELIOS-CR – a 1-D radiation-magnetohydrodynamics code with inline atomic kinetics modeling*, J. MacFarlane, I. Golovkin, P.R. Woodruff, JQSRT, Vol. 99, Issues 1-3, pp. 381-397 (2006)
[2] *Collisional-radiative spectral analysis code PrismSPECT* I. Golovkin, M. Feng Gu, J. MacFarlane, J. Sebald, T. Walton, High Energy Density Physics, v. 58, p. 101255 (2025)

**Presenting Author**

Dr. Golovkin is a Chief Technology Officer at Prism Computational Sciences – a company that develops and applies innovative software tools for scientific research and commercial applications in the physical sciences and engineering. His main focus of research has been on the study of plasmas created in high-power laser, z-pinch, and ion beam experiments performed at major national laboratories and universities. He leads the development of radiation-hydrodynamics and synthetic diagnostics simulation tools applicable to research in high-energy-density laboratory plasmas. Dr. Golovkin received his MS degree in mathematical physics from Moscow State University in 1993 and Ph.D. in atomic and plasma physics from the University of Nevada, Reno in 2000.

P86

# Investigation of Atomic Processes and Radiative Transfer in Tin Plasmas for Updating the Opacity Table (Invited)

Akira Sasaki[1,2], Atsushi Sunahara[2, 3], Katsunobu Nisihara[2], Yu Yamamoto[2], Nozomi Tanaka[2,4], Shinsuke Fujioka[2], Tomoyuki Johzaki[5], Kentaro Tomita[6], and Masashi Yoshimura[2]

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We investigate atomic processes and radiative transfer in tin plasmas as an extreme-ultraviolet light source for lithography. We develop the opacity table, which is used in the radiation hydrodynamics simulation to identify pumping conditions to obtain high output power and efficiency. We extend the temperature and density ranges of the table to optimize solid-state laser-pumped sources, based on the atomic structure and atomic processes of tin ions. The emission and absorption concerning the doubly and triply excited states of tin ions in high-density plasmas [1] are taken into account [2]. The detailed structure of unresolved transition arrays (UTA) from 4d-4f and 4p-4d transitions for 5 to 17 times ionized tin is included to calculate spectral emissivity and opacity, making the model applicable to higher temperatures.

[1] R. Schupp, et al. Phys. Rev. Appl. 12, 014010 (2019).
[2] A. Sasaki, Appl. Phys. Lett. 124, 064104 (2024).

**Presenting Author**

Akira Sasaki obtained Dr. Eng. from Tokyo Institute of Technology in 1991 and joined Japan Atomic Energy Research Institute, presently National Institutes for Quantum Science and Technology (QST), in 1996. He investigates the modeling of complex atomic processes and radiative transfer in plasmas to investigate EUV spectrum. He has developed a collisional radiative model based on computational atomic data and using statistical methods. He has been involved in the research projects for EUV lithography since 2003 for the analysis of emissions at $\lambda$=13.5nm from tin plasmas, and is also interested in shorter wavelength emissions from a variety of atomic elements using UTA and line emissions.

P87

# Optimization of EUV Output by Experimentally Validated Radiation-Hydrodynamic Simulations Across a Broad Laser Parameter Space (Invited)

Nozomi Tanaka[1,2], Yu Yamamoto[1], Akira Sasaki[1,3], Katsunobu Nishihara[1,4], Atsushi Sunahara[1,5], Tomoyuki Johzaki[1,6], Kentaro Tomita[7], Shinsuke Fujioka[1], and Masashi Yoshimura[1]

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With the introduction of extreme ultraviolet (EUV) lithography into high-volume semiconductor manufacturing, engineering issues such as wall-plug efficiency and system footprint have gained increasing attention. Solid-state mid-infrared lasers have been proposed as alternatives to current $CO_2$ driver. Since the optimum conditions for EUV generation depend strongly on laser wavelength, which affects the overall source dynamics, systematic exploration of the parameter space using a reliable simulation code is essential for re-optimization of the operating parameters. In this work, we performed a large-scale parameter survey of laser-produced tin plasma using the radiation-hydrodynamics code STAR1D, which has been validated against laser-plasma experiments. Simulations were carried out over a wide range of laser wavelengths and intensities while varying pulse shape and target size. Under the present simulation conditions, the highest CE obtained in this survey is 5.63% at a laser wavelength of 5.5 μm. Among possible driver wavelengths, mid-infrared lasers around 2 μm are considered realistic candidates. Our results indicate that the optimum parameters for EUV generation with a 2 μm driver are compatible with practical operating conditions of current 2 μm laser systems.

**Presenting Author**

Dr. Nozomi Tanaka received her Ph.D. in 2010 from Tohoku University, Japan, for research on energetic helium neutral beams for fusion diagnostics. She later shifted her research focus to extreme ultraviolet science at the Institute of Laser Engineering, The University of Osaka. Her research interests include the generation of intense pulsed XUV radiation and its interaction with materials for industrial applications. Beginning in 2019, she led a collaborative project between ILE and an international semiconductor company on tin debris cleaning using photoionized and photodissociated hydrogen atoms. She currently conducts radiation-hydrodynamic simulations to optimize the EUV source performance.

P91

# Applications of EUV Metrology Tools (Invited)

Matt Hettermann, Dave Houser, Chami Perera, Patrick Naulleau

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With the rapid adoption of EUV lithography, there is an increasing demand for actinic metrology and characterization equipment. EUV Tech provides an extensive suite of tools meeting these needs in the mask, pellicle, and resist space. These tools include a spectroscopic reflectometer for characterizing mask reflectivity and d-spacing, a pellicle measurement tool for ultra-high accuracy determination of pellicle transmission and reflection including spectral response. Additionally, EUV Tech now also provides a variable angle spectroscopic reflectometer/ scatterometer for the measurement of optical properties of materials in the EUV regime as well as film stack characteristics and phase both in blanket areas as well as within periodic structures allowing 3D and edge effects on the phase to be measured. Finally, EUV Tech has developed a compact zone plate-based microscope based on a discharge source. Previous implementations of such zone plate-based systems had been limited to synchrotron sources.

In this paper, we briefly describe the core technologies behind these tools and provide an overview of various applications including centroid shift across a mask due to multilayer coating process variation; transmission uniformity over an entire pellicle; actinic mask defect review; and the continual monitoring of phase stability in a manufacturing environment, which can provide invaluable knowledge about best practices for mitigating or reversing phase drift resulting from effects such as contamination and mask aging.

P93

# EUV-Generated Plasma Characterization Using a Transparent RFEA (Invited)

Jacqueline van Veldhoven, Arnold Storm, Sjoerd Goumans, Jurjen Emmelkamp, Dagmar Wismeijer, Peter Giesen, Peter van der Walle, Lucas Poirier, Cederik Meekes, and Henk Lensen

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In EUV lithography machines, both optical elements and construction materials interact with a combination of EUV light, radicals and plasma, resulting in both desirable and potentially undesirable effects. In order to be able to understand and thereby predict the type and magnitude of these effects, it is crucial that the conditions that are experienced by materials in an EUV scanner are well characterized. This will also allow for better tuning of exposure conditions when testing materials in offline setups.

In the past, the plasma of the EUV exposure facility EBL2 at TNO was characterized using a Retarding Field Energy Analyzer (RFEA). Using this sensor, the hydrogen ion flux and energy could be measured as a function of time after each EUV pulse. However, during the EUV pulse itself, EUV light entering the sensors caused secondary electron generation at the collector that disrupted the measurements. To prevent this from happening, a new sensor geometry was designed that allows for measurement of the ions while limiting the interaction of EUV light with the electrodes. This transparent RFEA (tRFEA) was modelled and tested at EBL2.

**Presenting Author**

Jacqueline van Veldhoven is a scientist at TNO. She acquired her PhD from the university of Nijmegen on the topic of molecular deceleration and trapping, after which she joined TNO to work on underwater acoustics and sea mine countermeasures. In 2013, she returned to the topic of chemical physics; her current research is within the field of nano-lithography with a particular interest in EUV, XPS and plasma.

P95

# Soft X-rays for the Inspection of Complex Nanostructures and Thin Layers

A. F. Herrero[1], V. Truong[1], H. Kirschner[1], P. Hönicke[1,2], and V. Soltwisch[1]

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The properties of nanostructured surfaces are determined by their composition, size and shape. The continuously shrinking dimensions of the features and their increasing complexity require non-destructive methods with high throughput that are able to asses complex 3D structures. Measurement techniques based on light-structure interaction allow a fast and non-destructive inspection of structured areas and are already widely used in the infrared, visible and hard X-ray spectral ranges. The German national metrology institute (PTB) is engaged at the storage rings BESSY II and MLS with the development of metrology in the UV to X-ray spectral ranges; the wavelength range from 0.12 nm to 50 nm is covered at different beamlines. PTB's radiometric capabilities allow accessing fluorescence, scattering and reflected signals in a quantitative and traceable manner. Computational methods are developed for the complete numerical simulation of the measurements, including parameters like beam divergence and energy spread. Those parameters as well as the assessment of optical constants of the materials in the soft X-ray range improve the reconstruction. We also investigate the combination of several methods, e.g. fluorescence and scattering simultaneously, so-called hybrid metrology, to enhance the robustness of the results.
Here, we give an overview of the existing experimental and computational tools for the characterization of nanostructures, as well as the ongoing developments.

**Presenting Author**

Analía F. Herrero has worked on the development of optical elements and metrology methods for synchrotron radiation during the last 12 years. She did her PhD thesis on the characterization of line-edge roughness on periodic nanostructures using soft X-ray scattering at the national metrology insitute in Germany, PTB. After a PostDoc at Helmholtz Zentrum Berlin developing optical elements for the EUV and soft X-ray energy region, she is back at PTB, where she develops metrology methods for the characterization of nanostructured surfaces.

P101

# The Development of EUV and Soft X-ray Optical Evaluation Systems in TOYAMA

Akira Miyake

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Toyama is developing various optical evaluation systems for the spectral range of EUV and soft X-ray, utilizing our technology and experience accumulated over more than 50 years in the development and manufacturing of X-ray optical systems and vacuum systems for synchrotron radiation facilities. In this presentation, we report on the following systems and discuss the required specifications of the light source for these systems.

(1) EUV multi-beam interference fine pattern exposure system
Interference exposure experiments using highly coherent synchrotron radiation light sources have been implemented to evaluate the resolution of resists. We discuss the possibility of implementing this exposure method using a compact plasma light source with low brightness and low coherence. Furthermore, we discuss strategies for the practical application of interference exposure using plasma light sources.

(2) EUV reflectometer
We are developing a stand-alone EUV reflectometer system that can evaluate the spectral reflectance of EUV multilayer mirrors with high accuracy. The reflectometer is equipped with a correction system so that it is not affected by fluctuation in the intensity and spectrum of the plasma light source.

(3) EUV irradiation test system: We are developing a high-intensity EUV irradiation optical system for evaluating the durability of EUV optical components and resist sensitivity and so on.

**Presenting Author**

Akira Miyake is a chief engineer at TOYAMA Co., Ltd. and is in charge of the optical design of X-ray optical systems. After studying X-ray astronomy at Osaka University, he joined Canon Inc. in 1987 and participated in the optical systems development of the X-ray and EUV exposure equipment. From 2015, he also participated in the development of large astronomical telescopes and satellite optical systems.

P102

# T4(THP)$_4$: Exploring Silicon-Based Inorganic Molecular Resists for Blue-X (6.7 nm) Lithography

Gahyun Lee[1], Hayun Kim[1], Seung-Yong Baek[1], Jiyoung Bang[1], Qi Zhang[2], Oleg Kostko[2] and Hyun-Dam Jeong[1]

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Current EUV lithography ($\lambda$ = 13.5 nm) relies on numerical aperture (NA) expansion up to Hyper–NA (0.75–0.77). However, because the depth of focus (DOF) scales inversely with $NA^2$, this approach inevitably results in severe DOF reduction, amplified stochastic variability, and significant manufacturability risks. For identical ~6 nm linewidths, Blue–X lithography ($\lambda$ = 6.7 nm) provides approximately two-fold larger DOF *at nearly half the NA* compared to Hyper-NA EUV lithography, dramatically relaxing optical constraints and improving process margins. However, this transition requires new resist materials, as photoionization cross sections and exposure chemistry differ fundamentally in the Blue–X regime. To address this challenge, we propose a silicon-based cyclosiloxane molecular resist, tetra(tetrahydropyranyl)-tetramethylcyclotetrasiloxane (T4(THP)$_4$), which provides a high photoionization cross section (25.2 Mb/molecule) at the Blue-X (6.7 nm). This is mainly due to the higher photoionization cross section (4.02 Mb/atom) of silicon element at the wavelength, compared to (1.02 Mb/atom) of Sn element. T4(THP)$_4$ exhibited higher e-beam and Blue-X (6.7 nm) open-frame sensitivities than tetrahydroxy-tetramethylcyclotetrasiloxane, owing to the versatile electron-driven chemistry of the THP groups, and also showed a larger total electron yield (TEY) than conventional resists such as CAR, PMMA, PHS, and MOR. Outgassing analysis revealed that numerous mass fragments originating from the THP groups are generated upon Blue-X (6.7 nm) exposure, which is consistent with the proposed electron-driven cross-linking mechanism responsible for chemical contrast formation in the T4(THP)$_4$ resist.

**Presenting Author**

Gahyun Lee received her B.S degree from the Department of Chemistry at Chonnam National University, and she is currently studying for a Ph.D. in the Department of Chemistry at Chonnam National University. Her research focuses on the development of inorganic molecular resists for EUV, Blue-X (6.7 nm) and Blue-X (3.1 nm) Lithography

P103

# Dynamic Covalent Assembly(DCA)-Zinc Oxo Cluster Resists for EUV, Blue-X (6.7 nm) and Blue-X (3.1 nm) Lithography

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Our laboratory has recently initiated research on architectural design strategies that connect molecular resist units, rather than modifying the molecules themselves, to enable inorganic molecular resists targeting 6 nm-class linewidths for Ångström-node semiconductor technologies. In this approach, inorganic resist molecules are interconnected prior to exposure through reversible covalent bonds that can revert to their original molecular state under specific chemical conditions. This dynamic linkage forms a molecular network that preserves solubility contrast between exposed and unexposed regions while maintaining highly uniform molecular arrangements, which is expected to reduce line-edge roughness (LER) and enable smaller minimum half-pitch. We refer to this concept as a dynamic covalent assembly (DCA)–inorganic molecular resist. To demonstrate this strategy, zinc oxo clusters (ZOCs) bearing amine and aldehyde ligands, ZOC-4ABA and ZOC-4FBA, were synthesized via ligand exchange from oxo(hexa(trifluoroacetato))tetrazinc. Mixing the two clusters resulted in rapid imine bond formation at room temperature after spin-coating onto silicon wafers, confirmed by FT-IR analysis, indicating efficient dynamic covalent assembly. The resulting DCA–ZOC resist exhibited a negative-tone electron-beam open-frame sensitivity of 70 μC $cm^{-2}$ at 5 keV. However, rapid precipitation due to high solution reactivity limited storage stability. By introducing new ligands into the ZOC structures, confirmed by $^{1}H$ NMR and FT-IR, solution stability was significantly improved and the sensitivity enhanced to 3 μC $cm^{-2}$ at 5 keV. Calculated molecular photoionization cross-sections were 88.0, 33.2, and 22.9 Mb $molecule^{-1}$ at EUV (13.5 nm), Blue-X (6.7 nm), and Blue-X (3.1 nm), respectively, indicating strong photosensitivity across these wavelengths.

**Presenting Author**

Hayun Kim received a B.S. degree from Chonnam National University, majoring in Department of Chemistry and double majoring in Semiconductor Convergence Major, and he is currently pursuing an M.S. in the Department of Chemistry at Chonnam National University. His research focuses on the development of inorganic molecular resists for EUV, Blue-X (6.7 nm) and Blue-X (3.1 nm) Lithography.

P104

# Synthetic and Process Optimization of the Tin-Oxo Cluster CNU-TOC-01 toward Improved EUV Lithographic Performance

Seungyong Baek, Soyeong Heo, and Hyun-Dam Jeong

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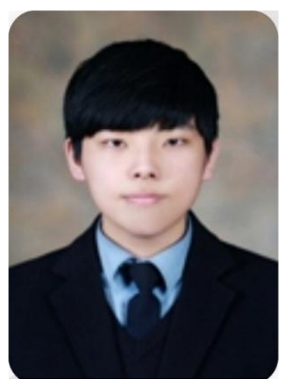
We previously reported the synthesis of CNU-TOC-01(4C-C), a tin-oxo cluster developed as an inorganic molecular resist for EUV lithography, at the 2024 EUV Workshop and subsequently in a 2025 publication in *Inorganic Chemistry,* which achieved a sensitivity (DtS) of 105 mJ/cm² and a resolution of 18 nm. However, the previously reported synthetic route exhibited poor reproducibility and frequently generated significant impurities, including species suspected to be undesired inorganic polymeric by-products. As a result, EUV pattern formation was inconsistent: in many cases the films were completely dissolved during development, and even when patterns were obtained, they exhibited poor line-edge roughness (LER) and unsatisfactory dose-to-size (DtS) characteristics. To address these issues, we systematically investigated several reaction conditions, primarily varying the internal reactor temperature and the amount of $H_2O$ reactant, in order to identify optimal conditions that suppress condensation reactions and the formation of polymeric byproducts. As a result, the electron-beam open-frame sensitivity improved from 10 μC/cm² in the earlier condition to 5.5 μC/cm² under the optimized condition (no $H_2O$ addition, 76 °C). Replacing the conventional 2.38% TMAH aqueous developer with 2-heptanone enables the PAB/PEB temperatures to be lowered from 185 °C to 130 °C without sacrificing electron-beam sensitivity. Furthermore, replacing pyrazole with 3,5-dimethylpyrazole, denoted as CNU-TOC-01(35-M) in our laboratory, further improved the electron-beam open-frame sensitivity to 3.5 μC/cm².

**Presenting Author**

Seung-Young Baek received his B.S degree from the Department of Chemistry at Chonnam National University, and he is currently studying for a M.S in the Department of Chemistry at Chonnam National University. his research focuses on the development of inorganic EUV photoresist.



P105

# CASILON: A Core–Arm Siloxane Molecular Resist Candidate for Blue-X (6.7 nm) Lithography

Hyun-Sung Yoon and Hyun-Dam Jeong

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A core–arm siloxane molecular network (CASILON), 2,4,6,8-tetrakis(4-ethynylstyryl)-2,4,6,8-tetramethylcyclotetrasiloxane, was synthesized via hydrosilylation of tetramethylcyclotetrasiloxane (TMCTS) with 1,4-diethynylbenzene in the presence of Karstedt's catalyst. The cyclotetrasiloxane core is advantageous for Blue-X (6.7 nm) lithography because silicon exhibits a relatively large photoionization cross section at this wavelength, while the cyclic inorganic framework provides enhanced mechanical stability. In addition, the ethynyl groups in the arm structures are potentially both photo-reactive and thermally cross-linkable, which may be beneficial for resist applications. The molecular structure was characterized by $^{1}H$ NMR, FT-IR, and ESI-MS. The linear absorption coefficient at 6.7 nm was estimated from the film density and molecular photoionization cross section. The e-beam open-frame sensitivity was measured to be 6.0 μC/cm² using isopropyl alcohol as the developer. Electron-beam lithography was further performed to preliminarily investigate the lithographic behavior and potential issues associated with ethynyl-functionalized arm structures when applied as an inorganic molecular resist.

**Presenting Author**


Hyun-Sung Yoon received his B.S. degree in Chemistry with a double major in Semiconductor Convergence from Chonnam National University. He is currently studying for a M.S. degree in the Department of Chemistry at Chonnam National University. His research focuses on the development of inorganic molecular resists for EUV, Blue-X (6.7 nm) and Blue-X (3.1 nm) Lithography.

P106

# Photoresists Beyond EUV: Revisiting X-ray Nanocomposite Resists - For Potential BEUVL

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Novel organic inorganic nanocomposite resists: Engineered to reduce proximity effects, high contrast and sensitivity, superior etch resistance. Molecular architecture of these resists (specific) for X-ray lithography and by extension for potential BEUV.

[1] *Gonsalves et al Jan 2000 JVST Microelectronics Processing & Phenomena 18(1): 325-327 doi: 1116/1.591193*

**Presenting Author**

Kenneth E Gonsalves is currently Guest Professor of Electrical Engineering at IIT Gandhinagar. He was also the Celanese-Acetate Distinguished Professor at UNC @ CLT and Visiting Distinguished Professor at IIT Mandi. He held the position of Associate Director ONRG USA DoD Americas. His research has focused on multi-wavelength nanopatterning for lithography from DUV to EUVL supported by industry and US and overseas funding agencies.

P107

# Tabletop Extreme Ultraviolet (EUV) Testing Platform for Lithography Materials

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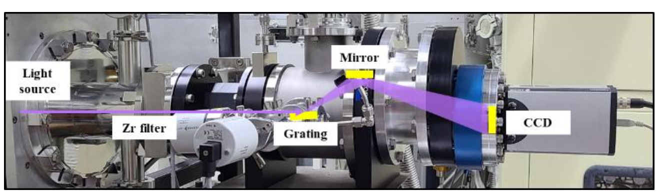
With the widespread adoption of IT technologies requiring rapid processing of massive datasets, such as artificial intelligence and autonomous driving, the performance requirements for semiconductor devices with high-speed computing capability and large storage capacity have increased significantly. At the same time, continued scaling of device design rules has accelerated the adoption of extreme ultraviolet (EUV) lithography, which enables the formation of sub-76 nm pitch patterns in a single exposure process. The expansion of EUV lithography has increased the demand for EUV-related materials, including photoresists, pellicles, filters, and optical components, creating a strong need for instrumentation capable of precise optical characterization of these materials.

In this work, we developed an evaluation platform for EUV lithography materials based on a discharge-plasma Z-pinch EUV source, as shown in Fig. 1. By optimizing the discharge parameters of the Z-pinch plasma source, the optical power was maximized, and an exposure evaluation method was established to assess the sensitivity of photoresists. In addition, analysis of the EUV output demonstrated that the transmittance of EUV optical filters can be measured with high precision. This platform can provide rapid and accurate characterization of prototype EUV exposure materials such as photoresists and pellicles.




[Fig.1] Experimental setup for EUV source evaluation.

[1] G. Tallents, E. Wagenaars, and G. Pert, "Lithography at EUV wavelengths," Nature Photon. 4, 809–811 (2010).

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# Performance of EUV Light Source with Cold Field Emitters (CFEs) Beam Irradiation Technique

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We developed novel EUV light source with cold field emitters (CFE) electron source irradiation technique. The CFEs with fully vertically aligned electron sources shows very unique properties, such as collimated electron trajectories, high brightness, reliable and stable electron emission current, simplicities of operation etc. The EVV sources with the CFE show very stable operation, easiness in beam form shaping, smallest in FWHM (Full Width at Half Maximum) and compact design. The lighting performance depending on the collimation lens design. We evaluated the EUV transmittance of CNT membrane pellicles, and give very reliable data.

In this presentation, we will report on the compact structure of EUV light source, lighting performance of the light and application for the EUV components inspections.

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# Dynamics of Pre-Pulsed Laser-Produced Plasmas Generated Using Mass Limited Sn Targets

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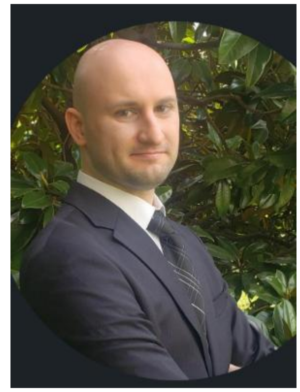
The mass-limited nature of Sn droplets used in commercial EUV lithography systems improves radiation transport, allowing the shape and density of the target formed during the pre-pulse stage to be optimized for maximizing the conversion efficiency (CE) of 13.5 nm emission while minimizing debris. Similar mass-limited targets can also be produced through alternative approaches, such as foils, low-concentration targets, liquid spray systems, and others. Understanding and controlling the radiation transport in plasmas generated on mass-limited targets - through plasma characterization - is an important consideration for both current and next-generation beyond EUV (BEUV) light sources.

In the present work, mass-limited Sn foil and low-concentration foam targets were irradiated using 6 ns FWHM, 1064 nm Nd:YAG laser(s). Measurements of EUV emission intensity from foil, foam, and bulk Sn target plasmas were compared with and without pre-pulsing. The dynamics EUV-emitting plasma were characterized and compared using a combination of interferometry and Faraday cup ion studies. Relative ablation rates from foil and solid targets were determined using Faraday cup ion signals and crater measurements. Theoretical simulations obtained using the 1D radiation-hydrodynamics code HELIOS were used to better understand the evolution of the plasma properties and the EUV emission characteristics of the targets.

**Mathew Polek**



Mathew Polek received a Doctorate degree in Engineering Physics from the University of California San Diego (UCSD) in 2025. While studying at UCSD, he pursued research in laser produced plasmas under the mentorship of Dr. Sivanandan Harilal and Dr. Farhat Beg while working remotely at Pacific Northwest National Laboratory (PNNL). During his studies, Mathew published articles on various topics including fundamental plasma physics, laser induced breakdown spectroscopy, plasma diagnostics, and others. After graduating, Mathew joined PNNL as a post-doctoral research associate. He is currently researching extreme ultraviolet (EUV) lithography, ion acceleration, laser-induced breakdown spectroscopy, and more.

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# Multi-Diagnostic Experimental Characterization of Laser-Produced Tin Plasmas

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Extreme ultraviolet (EUV) lithography at 13.5 nm, driven by laser-produced tin (Sn) plasmas, has become the foundational technology in semiconductor manufacturing. A primary challenge is the control of plasma parameters: electron density, electron temperature, and ion charge state distribution, which define the spectral purity and conversion efficiency of the EUV source. Here, we present our experimental and modeling efforts on comprehensively characterizing laser-produced tin plasmas and the resulting EUV emission.

We introduce 'SparkLight', a new platform for generating and characterizing laser-produced plasmas. Tin plasmas are generated by irradiating a continuously moving tin-coated wire with a 1064 nm Nd:YAG laser. The facility integrates three complementary diagnostics: EUV emission spectroscopy, laser interferometry, and coherent Thomson scattering.

We devote particular attention to Thomson scattering, which allows for space- and time-resolved characterization of laser-produced plasmas. To reject stray light and isolate Thomson signal from the plasma self-emission, we utilize a compact and cost-effective design based on a Wollaston prism, volume Bragg grating notch filters, and a single-grating spectrometer.

This work demonstrates an integrated and practical approach for characterization of plasmas in EUV source development.

**Presenting Author**

Stanislav Musikhin is an Associate Research Physicist at the Princeton Plasma Physics Laboratory (2022—present) working on low-temperature plasma diagnostics and their use for synthesis, and modification of nanomaterials. Recently, he expanded his diagnostics portfolio to include coherent Thomson scattering applied to tin laser-produced plasmas. During his graduate studies (2018—2022) at the University of Waterloo and the University of Duisburg-Essen, Stanislav investigated the gas-phase synthesis of graphene using various in situ diagnostics.

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# Development and Evaluation of Free-standing Mo/Si Multilayer Beam Splitters

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Beam splitter (BS) is one of the powerful optical components for many optical inspections such as reflectometers, interferometers, and interferometric microscopies. Although there are several reports about free-standing or membrane support Mo/Si multilayer BSs around 13.5nm region, they are still in the fundamental research stage, and their applications are limited to experimental purpose.

In this work, we have developed and evaluated free-standing Mo/Si multilayer BSs including optical design flexibility and long-term stability for the industrial applications. BSs were fabricated based on SiN membrane formation process, Mo/Si deposition process, and SiN etching process. To evaluate the design and fabrication flexibility, three types of BSs were developed, and their reflectivity and transmittance profiles were measured by a reflectometer at Advanced Light Source BL6.3.2. In addition, we measured the reflectivity and transmittance of an EUV BS at both as-fabricated and after 3-years kept in dry-nitrogen environment for demonstration of long-term stability. These results show that the free-standing Mo/Si multilayer BSs will be useful for not only fundamental research but for industrial applications.

**Presenting Author**

Masatoshi Hatayama is the Global Sales Manager for Material and Nanotechnology Business at NTT Advanced Technology Corporation (NTT-AT). He joined NTT-AT in 2003 and developed EUV and x-ray optical components for high-order harmonics applications, synchrotron science, and EUV lithography related fields. He received his Ph D. in engineering from Saitama University in 2010.

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# Maximize EUV and BEUV Instrument Performance with Custom Blazed, Variable-Line-Space Reflection Gratings on Flat or Curved Surfaces

Samuel Gleason, James Lee, Subha Kumar, Nick Toombs, Cody Jensen, and Peter Abbamonte

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Diffraction gratings provide fine control over the wavelength of light used in optical systems. Blazed reflection gratings are especially desirable for EUV applications because they can achieve both high spectral resolving power and high efficiency at 13.5 nm. Inprentus creates custom blazed reflection gratings using a unique nano-ruling method that allows us to make metal master gratings with arbitrary groove profiles with high precision. Our method is ideally suited for the manufacture of variable-line-space (VLS) gratings, which combine spectral dispersion and focusing into one optic. We recently demonstrated the ability to produce EUV gratings on concave substrates, which could be used to optimize plasma light sources in real-time to improve semiconductor patterning efficiency and yield. Inprentus' metallic master gratings are inherently ultra-high vacuum (UHV) compatible, radiation-hard and mechanically robust giving significant advantages over transmission gratings. This poster summarizes Inprentus' capabilities in grating design, manufacturing, and characterization.

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