Workshop Abstracts

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Ricardo Ruiz (LBL)

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Abstracts

for

2024 EUVL Workshop
and
Supplier Showcase

Listed by abstract numbers

P1

New Development of EUV Materials and MI solutions for High NA Mask (Keynote)

In-Yong Kang, Sukjong Bae, Sanguk Park, Hyonseok Song, Jin Choi

Samsung Electronics Co., Ltd. (Republic of Korea)

The introduction of High NA EUV scanners is expected to cause many changes in the structures of EUV masks and related equipment. Specifically, new materials used for High NA masks can enhance the EUV mask performance, and EUV pellicles are actively improving based on CNT membranes. In addition, Measurement and Inspection (MI) technologies for High NA masks have faced challenging situations, and many companies are developing new solutions. In this presentation, we will show our current achievement for High NA EUV masks and related equipment.

Presenting Author

In-Yong Kang received his Ph. D. degrees from the Hanyang University in Materials Science and Engineering in 2008. He started at Samsung Electronics in 2008 and has worked on various topics related to EUV mask development. He is currently working as Group Leader of Advanced Technology Group in Mask Development Team with focus on new EUV materials and equipment for High-NA mask.

P2

Pushing for Record Reflectivities for Short Wavelength Multilayers – EUV and Beyond (Keynote)

Marcelo Ackermann

University of Twente

Presenting Author

Marcelo Ackermann is chair of the Industry Focus Group – X-ray and EUV (XUV) optics at the MESA+ institute of the University of Twente. He obtained his PhD in physics (cum laude) in 2007 on a shared research project between Leiden University and the ESRF in Grenoble, under the guidance of Prof. Frenken and Prof. Ferrer. After that he held different leading positions in industrial research for the development of X-ray, visible and IR optics at cosine Research, Helbling Technik, SCHOTT Advanced Optics and ASML. In 2020 he re-joined academia as full professor in the XUV group, focusing on the development of next generation reflective, refractive and transparent X-ray and EUV optics in collaboration with industrial partners like Zeiss, ASML and Malvern Panalytical.

P3

The Next Step in Moore's Law: High NA EUV Imaging and Overlay Performance (Keynote)

Jan van Schoot[1], Sjoerd Lok[1], Rob van Ballegoij[1], Eelco van Setten[1], Guido Schiffelers[1], Rudy Peeters[1], Jara Garcia SantaClara[1], Peter Vannoppen[1], Paul Graeupner[2], Peter Kuerz[2], Thomas Stammler[2]

[1]ASML Netherlands B.V. (The Netherlands)
[2]Carl Zeiss SMT GmbH (Germany)
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At this moment EUV systems equipped with a 0.33 Numerical Aperture (NA) have proven themselves and are successfully applied in high volume manufacturing. The next step is 0.55 NA and is ready to enter mass production. This so-called high NA scanner, targeting an ultimate resolution of 8nm, will bring multiple benefits to the semiconductor market such as reduction of process complexity, yield improvement, higher resolution enabling printability of smaller features at increased density, and cost of technology reduction. It will extend Moore's law for at least another decade. A novel lens design, capable of providing the required Numerical Aperture, has been identified; this so called anamorphic lens will provide 8nm resolution in all orientations. Paired with new, faster stages and more accurate sensors providing the tight focus and overlay control needed it enables future nodes. In this paper, an update will be given on the status of the imaging and overlay performance of this exposure tool. The results are taken from the first tool that resides in the High NA lab.

Presenting Author

Dr. Jan B.P. van Schoot, is Director of System Engineering and Technical Specialist at ASML, based in Veldhoven, The Netherlands. After his study Electrical Engineering (Cum Laude) at Twente University of Technology. He received his PhD in Physics on the subject of non-linear optical waveguide devices in 1994 and held a post-doc position studying waveguide based electro-optical modulators. He joined ASML in 1996 and was Project Leader for the Application of the first 5500/500 scanner and its successors up to 5500/750. In 2001 he became Product Development Manager of Imaging Products (DoseMapper, Customized Illumination). In 2007 he joined the dept of System Engineering. He was responsible for the Optical Columns of the 0.25NA and 0.33NA EUV systems. After this he worked on the design of the EUV source. He was the study leader of the High-NA EUV system and is now responsible for the High-NA optical train. He is a Fellow of the SPIE, holds over 35 patents and presents frequently at conferences about photolithography.

P4

High-NA EUV: An Update on Introduction (Keynote)

Steve Carson

Intel Corporation

Extreme Ultraviolet lithography 0.33 NA scanners are the established platform for leading process node critical layer patterning. Initial 0.33NA EUV adoption simplified integrated process strategies with respect to earlier multi-patterning 193i technologies. Near horizon nodes are already employing multi-patterning schemes utilizing 0.33NA EUV. Multi-patterning schemes carry an increased process cost and introduce integration complexity. High-NA (0.55NA) EUV provides enhanced image contrast and improved resolution, and while High-NA EUV introduces new technology challenges in insertion, the paradigm changes are few as compared to the transition from 193i lithography to 0.33NA EUV. Many of the learnings realized for 0.33NA EUV are transferrable to 0.55NA lithography, simplifying the early deployment of the platform. The anamorphic optical design of the High-NA scanner results in half-field imaging, introducing new risks at the lithographic step and in the overall process integration scheme. This presentation will review the status of High-NA lithographic equipment, the surrounding ecosystem, and its readiness for introduction into manufacturing.

Presenting Author

Steven L Carson is a Principal Engineer at Intel Corp. Steve joined the Photolithography department in Intel’s Portland Technology Development organization in 1999 after completing a B.S. degree at the California Institute of Technology, and M.S. and Ph.D. degrees at the University of Florida, all in Chemical Engineering. He has been involved with developing stepper and scanner platforms from i-line to EUV for integration into high volume manufacturing. He has also been involved in the development of advanced process control (APC) applications and factory automation systems, earning patents in both. Since 2008, Steve has primarily focused on EUV imaging and its collateral technologies including the scanner, the source, EUV reticles, and EUV pellicle membranes.

Full Lifetime EUV Cost vs Performance for DRAM (Keynote)

Stephen D. Snyder

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EUV Lithography is widely used for CMOS Logic manufacturing. DRAM manufacturing adoption has been slower, but all three of the major DRAM manufacturers have committed to EUV for DRAM manufacturing.[1] The main roadblock for increased DRAM usage of EUV is cost vs performance. Applications that include relaxed pitch 2D features and sparse contact holes, unresolvable by double 193i exposure, scale nicely with EUV. However, the dense, regular line-space, contact hole or pillar features pervasive in DRAM memory arrays quickly become non-competitive with performance or cost. Great advancements have been made to improve resolution and throughput for EUV. However, there needs to be a dedicated focus towards cost-of-ownership items that may be affected by the increasing power and dose-to-size roadmap. The industry is moving through exciting inflection points for GAA/BSPR Logic manufacturing, High-NA EUV introduction and 3D DRAM manufacturing. Total lifetime cost vs performance and time to solution will continue to drive the patterning roadmap through these transitions and beyond.

[1] Shilov, Anton, "Micron to Bring EUV to Japan: 1γ Process DRAM to Be Made in Hiroshima in 2025." https://www.anandtech.com/show/18866/micron-to-bring-euv-to-japan-1-gamma-dram-to-be-made-in-hiroshima-in-2025, 19 May 2023.

Presenting Author

Stephen Snyder graduated with a Ph.D. in physics from University of Minnesota (Minneapolis, MN) in 2012 and *summa cum laude* with a B.S in physics and theoretical physics and applied mathematics from Loyola University Chicago (Chicago, IL) in 2006. Current position as SMTS - Photolithography Pathfinding (Boise, ID) at Micron focuses on manufacturing intercepts for advanced patterning processes in DRAM, NAND and CMOS technologies, specifically focusing on Photomask design and manufacturing, EUV process enhancements and post processing development for DRAM applications. Previous position with Intel Corporation from 2012 – 2020 as a Senior Module and Yield Enhancement Engineer focused on patterning processes for low metals/contacts and fin patterning for FinFET and RibbonFET technologies. Research interests include exotic patterning processes to reduce EPE, EUV lithography, advanced EUV mask processes, process modeling and CMOS/DRAM transistor architecture. Dr. Snyder is a lifetime member of SPIE, a collaborator with the IMEC AP3 program, holds four US patents, was honored to be a keynote speaker at the 2021 EUV Litho Workshop.

P6

Current Status and Technical Issues of the EUVL and Prospect for the Next Generation EUVL (Keynote)

Takeo Watanabe

Hyogo University

Abstract

Presenting Author

Takeo Watanabe received his Ph.D. from Osaka City University in 1990. He is Full Professor, Director of Center for EUV, and Dean Laboratory of Advanced Science and Technology for Industry, Executive Advisor to the President, University of Hyogo. He is an expert of the EUV lithographic technology, including optics, exposure tool, mask and resist related technologies. He has authored over 250 technical papers, and he is the president of the International Conference of Photopolymer Science and Technology (ICPST). He is also Conference Chair of the International Conference of Photomask Japan (PMJ). And he is a program committee member of the International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN). Furthermore, he is a committee member of lithography of IRDS.

Computing Beyond Moore’s Law (Keynote)

John Shalf

LBL

Moore’s Law is a techno-economic model that has enabled the information technology industry to double the performance and functionality of digital electronics roughly every 2 years within a fixed cost, power and area. Advances in silicon lithography have enabled this exponential miniaturization of electronics, but, the fabrication costs continue to rise, the classical technological economic model that has underpinned Moore’s Law for 50 years is becoming more challenging. The leading-edge is now accessible primarily to a handful of the most profitable companies and applications. This article provides an updated view of what a post-exascale system will look like and the challenges ahead, based on our most recent understanding of technology roadmaps. It also discusses the tapering of historical economics, and how it affects options available to continue scaling of successors to the first exascale machine. Lastly, this article covers the many different opportunities and strategies available to continue computing performance improvements in the absence of historical technology drivers.

Presenting Author

John Shalf is the Department Head for Computer Science at Lawrence Berkeley National Laboratory. He is also the 2024-2027 distinguished lecturer for the IEEE Electronics Packaging Society. He also formerly served as the Deputy Director for Hardware Technology on the US Department of Energy (DOE)-led Exascale Computing Project (ECP) before he returned to his department head position at LBNL. He has co-authored over 100 peer-reviewed publications in parallel computing software and HPC technology, including the widely cited report “The Landscape of Parallel Computing Research: A View from Berkeley” (with David Patterson and others). Before coming to Berkeley Laboratory, John worked at the National Center for Supercomputing Applications and the Max Planck Institute for Gravitation Physics/Albert Einstein Institute (AEI), where he co-created the Cactus Computational Toolkit.

P11

EUV Tech n/k Tool

Stuart Sherwin

EUV Tech

EUV lithography is rapidly being pushed to its resolution limit, where physical dimensions on the photomask including film thicknesses and sidewall profiles must be qualified to the sub-angstrom level. Actinic metrology at or near 13.5nm is promising, both because the wavelength is on the scale of dimensions being probed, and furthermore because actinic metrology is sensitive to precisely the physical effects that impact EUV scattering and therefore imaging. We discuss the suitability of the EUV Tech ENK (EUV n/k tool) for fully characterizing EUV photomasks in terms of the materials, film thicknesses, phase shift, and sidewall profile. We demonstrate how, using spectroscopic hyperspectral reflectometry and scatterometry driven by an LPP plasma EUV source, ENK is able to probe physical dimensions and material properties on the mask to the scale of angstroms and below.

Presenting Author

P12

Effects of EUV Multilayer Roughness in High NA EUV Lithography

Luke Long[1], Stuart Sherwin[1], Matt Hettermann[1], Patrick Naulleau[1]

[1] *EUV Tech*

As the industry continues to push the resolution limits of extreme ultraviolet lithography, seemingly subtle effects can have surprisingly large consequences. One such example is mask multilayer roughness, which has recently been shown to be a possible cause of significant local best focus shifts observed in aerial image measurements of contacts on NA33 masks. In this paper, we extend this analysis to NA55 masks, where in addition to a decrease in target feature size, anamorphic magnification causes anamorphic mask side defocus effects. We examine the effect for both traditional tantalum masks, as well as the increasingly interesting ruthenium attenuated phase shift masks, with an emphasis on the impact on aerial image local critical dimension uniformity.

Presenting Author

P14

Mask-side Hyper-NA imaging on the SHARP EUV mask microscope

Markus Benk, Ryan Miyakawa, Weilun Chao, Bruno La Fontaine

Lawrence Berkeley National lab, 1 Cyclotron Road, Berkeley, CA 94720

The first High-NA scanners are expected to enter high-volume manufacturing in 2026. Work towards Hyper-NA, the ultimate generation of EUV lithography is already underway.[1] At Hyper-NA, the increased range of incidence angles on the photomask creates new challenges. Multilayer coatings need to support an increased angular bandwidth. The oblique angle of incidence and enlarged angular range increase mask-3D effects. Alternative mask architectures and novel absorber materials are under investigation. Achieving low k1 factors for High-NA and Hyper-NA requires complex mask designs that may include sub-resolution assist features with challenging feature sizes. There is a critical need for instrumentation that can address these challenges. SHARP is a synchrotron-based EUV microscope dedicated to photomask research. SHARP emulates the mask-side numerical aperture, imaging conditions and illumination settings of current and future EUV lithography scanners. In 2015, almost ten years before the advent of the first High-NA scanner, anamorphic imaging at 0.55 4x/8xNA became available on the SHARP microscope. This year, we are implementing mask-side Hyper-NA imaging on SHARP, thus enabling the experimental investigation of mask-related research questions pertaining to Hyper-NA, years ahead of the introduction of the corresponding technology nodes. We will present an imaging study comparing 0.55 High-NA and 0.75 Hyper-NA imaging.

[1] I Lee, J-H Franke, V Philipsen, K Ronse, S De Gendt , E Hendrickx, JM3 22 (4), 043202 (2023)

Presenting Author

Markus Benk is the lead scientist of the CXRO EUV mask research and development beamline at Lawrence Berkeley National Laboratory. He received his diploma in photo engineering from the Cologne University of Applied Sciences in 2006 and his PhD from RWTH Aachen University in 2011. His current research interests include sources, metrology and optics for soft x-rays, and extreme ultraviolet light.

P15

Ion Beam Deposition over Larger Form-Factor EUV Mask Blanks (Invited)

Katrina Rook

Veeco Instruments, 1 Terminal Drive, Plainview NY 11803

State-of-the-art EUV photomask blanks have area dimension 6” x 6” and are coated with an ion-beam-deposited multilayer of Mo/Si, specifically designed for maximum reflectivity at the 13.5nm EUV wavelength. The within-mask uniformity requirement for current EUV blanks is +/- 0.015nm range of Central Wavelength (CWL), requiring film uniformity of approximately 0.2% across the active 104mm x 132mm area. Due to the advancement of anamorphic projection, and to avoid pattern-stitching, larger form-factor EUV masks are being considered. The active area is designated to stretch to 104mm x 264mm. Mask shape proposals include 300mm round, 6” x 12” rectangle or 6” x 11.2” rectangle. A key enabler of larger form factor is the capability to deposit high-performing Mo/Si multilayer mirrors over the larger area.

We present simulations and data for the uniformity performance of the Veeco ion beam deposition tool over the double-sized active area. Molybdenum, Silicon and Ruthenium are all included. We demonstrate that the non-uniformity of today’s processes-of-record could result in 2.2x higher nonuniformity over the doubled active area, implying CWL uniformity of +/- 0.03 nm. We here present the latest large-area EUV reflectivity results, exhibiting CWL uniformity of +/- 0.04 nm. We then discuss process and hardware modifications which are simulated to enable CWL uniformity recovery to better than +/- 0.015 nm over the 104 mm x 264 mm size.

Presenting Author

Dr. Katrina Rook is Principal Process Engineer with the Advanced Deposition and Etch division of Veeco Instruments. Katrina has 35 years’ experience in thin-film processing and characterization techniques. She received her MS and PhD in Physics from Carnegie Mellon University, where she investigated magnetic film deposition and ferromagnetic resonance. Her magnetic film research continued during her early career, and after joining Veeco she had the opportunity to expand also into ion beam etch and into a variety of film applications. Since 2017, she has become engaged in development of EUV mask-blank and EUV pellicle processes.

P18

Integrating Actinic EUV Research with Advanced Analytical Technologies (Invited)

Sangsul Lee

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In addressing the complexities of sub-7nm semiconductor manufacturing, the integration of actinic metrology with advanced analytical techniques is pivotal. We focus on optimizing EUV components like photoresists and pellicles, using Nano-IR spectroscopy and ambient pressure X-ray Photoelectron Spectroscopy (AP-XPS) for material behavior insights including photon stochastic. Alongside, we develop metrology for high-NA EUV systems at 13.5nm wavelength. We further enhance our research with synchrotron radiation and high harmonic generation (HHG) for detailed analysis of EUV photoresists and pellicles, crucial for their improvement. Additionally, we highlight POSTECH's advanced EUV infrastructure, including synchrotron and HHG facilities in semiconductor technology advancements.

Sangsul Lee

Sangsul Lee is a scientist at the Pohang Accelerator Laboratory (PAL) and an affiliate professor in the department of semiconductor engineering at POSTECH. He has actively pursued research in EUV mask, resist and actinic EUV metrology and inspection technology. His research interests include EUV research utilizing various EUV and X-ray sources, complemented by techniques such as nano-IR spectroscopy, AP-XPS, and X-ray tomography

P19

Efforts in the Development of EUV Masks within the Context of a Merchant Mask Shop

Hiroki Deguchi

Fine Device Operations,
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EUV lithography is an extremely important technology for advanced scaling in semiconductor manufacturing. It is currently undergoing high volume manufacturing (HVM) of 3 nm logic node and development of 2 nm node by leading-edge semiconductor manufacturers. It is expected that further miniaturization will continue to A10 technology and beyond. EUV masks play a crucial role as a supporting technology for EUV lithography and are essential for realizing device manufacturing.

Since 2016, DNP has been engaged in the development of EUV masks utilizing MBMW. As a merchant mask shop, we have been diligently addressing a variety of customer requirements. In this paper, we will concentrate on elucidating the following endeavors undertaken by DNP.

- Resolution capability of EUV masks using the latest chemically amplified resist
- Exploration of the potential application of alternative resist to EUV masks
- Various material capability of DNP mask process.
- Future prospects of EUV masks as a merchant mask shop.

Presenting Author

Hiroki Deguchi is a manager of Dai Nippon Printing Co., Ltd Photomask sales Division. He received a master’s degree in mechanical engineering from the Kanazawa University, Ishikawa, Japan. He joined DNP in 2002 for photomask integrate Div. Currently, he is responsible for providing technical support for EUV masks at DNP.

P20

Study of Enhancing Etching Performance of Pt-based Absorber Material for EUV Mask

Seungho Lee, Dongmin Jeong, Yunsoo Kim and Jinho Ahn

Hanyang University, Seoul, 04763, Republic of Korea
CH^{3}IPS (Center for Hyperscale, Hyperfunction, Heterogeneous Integration Pioneering Semiconductor Technology)

EUV lithography is being developed for a high-NA system to enable future 3 nm nodes [1]. Since the conventional TaBN mask exhibits low mask performance, including NILS (Normalized Image Log Slope) and DoF (Depth of Focus), in the high-NA system, there is a need for research into new absorber materials. Pt (Platinum) has been actively studied as a promising alternative absorber material due to its superior imaging properties, but Pt faces challenges in mask pattern fabrication due to its low volatility during dry etching. In this study, we propose methods to enhance the etching performance of Pt-based EUV masks.

We alloyed Pt with W (Tungsten), which forms highly volatile reaction products, to address the low reactivity of Pt. Additionally, we applied an ion implantation process using Ar (Argon) to alleviate bonding energy by reducing crystallinity. The etching evaluation was conducted with ICP-RIE (Inductively Coupled Plasma-Reactive Ion Etching) using $CF_4/O_2/Ar$ gas. As a result, the etch rate of the implanted Pt-W alloy increased by 2.8 times compared to pure Pt under the same etching conditions, and XPS analysis revealed no residue detected on the surface after etching.

[1] R. Peeters, “High NA EUV: development towards introduction at the customer”, SPIE proc. 12494, 1249404 (2023)

Presenting Author

Seungho Lee is currently pursuing a Ph.D. in Materials Science and Engineering at Hanyang University under the supervision of Professor Jinho Ahn. His research focuses on advanced EUV masks for high-NA systems, particularly the optical simulation to explore new absorber materials and structural characteristics

P21

Experimental Investigation of the Mask Diffraction Obstructed by the Critical-sized Sn Particles on EUV Pellicle

Seungchan Moon, Dong Gi Lee, Junho Hong and Jinho Ahn

Hanyang University, Seoul, 04763, Republic of Korea
CH^{3}IPS (Center for Hyperscale, Hyperfunction, Heterogeneous Integration Pioneering Semiconductor Technology)

Recently, chip makers have adopted the EUV pellicle to mitigate yield reduction caused by the particle issue originated from the Sn droplet of LPP source. However, it has been reported that, if a particle on the pellicle (PoP) exceeds the critical size (>10 um), unacceptable wafer defects can occur [1].

In this study, it was experimentally confirmed that the lithographic effect of critical-sized PoP differs depending on the mask pattern by using through-pellicle mask imaging system of EUV ptychography microscope, an actinic mask inspection tool. We captured far-field diffraction patterns with and without 10 um Sn PoP obstruction for both Horizontal-line and space (H-L/S) and Contact hole (C/H) masks. As each mask diffraction order was absorbed and scattered by PoP, its intensity decreased by up to 4.031%, and the distribution spread by up to 164.08%. From the diffraction patterns, mask pattern images were reconstructed via a ptychographic algorithm, and then compared. As a result, the lithographic effect of critical-sized PoP on H-L/S pattern was 3 times more severe than that on C/H pattern. Eventually, the critical size of PoP should be determined depending on the mask pattern, and more strict criteria should be applied to the L/S pattern.

[1] M. Kupers, "Particle on EUV pellicles, impact on LWR", SPIE proc. 11147, 111470S (2019)

Presenting Author

Seungchan Moon is currently pursuing a PhD in nanoscale semiconductor engineering supervised by professor Jinho Ahn at Hanyang university (Republic of Korea). Moon is developing an EUV ptychography microscope for actinic patterned mask inspection and investigating the effects of EUV pellicle defects on mask imaging performance via through-pellicle mask imaging.

P22

Status and Outlook of EUV optics at ZEISS (Invited)

Martin Kaumanns, Jens Timo Neumann, Olaf Conradi, Paul Graeupner

Carl Zeiss SMT GmbH, Rudolf-Eber-Str. 2,
73447 Oberkochen, Germany

When Gordon Moore predicted that the number of components per integrated circuit will double every two years, who would have thought that even after almost 60 years his statements serve well as guideline for the semiconductor industry?

With the introduction of EUV lithography, Moore’s law could stand the test of time. And with well over 200 EUV scanners shipped and installed, EUV lithography became a high-volume-manufacturing reality and the key enabler for the latest generations of chips. For the established NA 0.33 platform, ASML and ZEISS continues to fulfill the chip makers’ demands with their newest upgrades, while enabling ever-increasing throughputs.

With the first shipments of NA 0.55 optics to ASML, and the shipment of the first NA 0.55 scanner to a chip maker, a new chapter has been opened for the future of EUV lithography. With the increase of NA from 0.33 to 0.55, the NA 0.55 platform optically resolves 8nm half-pitch for single-exposure securing the future of Moore’s law. This presentation shows the newest progress in the NA 0.33 optics and gives an overview on the NA 0.55 optical column system concept. Finally recent developments and ongoing activities at ZEISS and ASML are reported.

Presenting Author

2014-2021: Research associate for high power laser sources at the Ludwig Maximilian University of Munich, Germany

2020: PhD in Physics (Ludwig Maximilian University of Munich)

Since 2021: Scientist for EUV lithographic imaging at Carl Zeiss SMT

P23

Computational Lithography Solutions for High NA EUV with Mask Stitching (Invited)

Michael Lam

Synopsys

After many years of development and improvement, low-NA EUV has become a critical, enabling step in leading-edge semiconductor manufacturing. Now a new set of challenges present themselves to the industry as we look to achieve even higher resolution with 'high-NA' EUV tools. One area where several design and process challenges are expected is the need for double exposure mask stitching due to the reduced field size of high-NA scanners. Fortunately, computational lithography solutions for high-NA tools exist, and can accelerate process learning and physical design optimizations even prior to widespread access to high-NA scanners. This paper will discuss extensions to computational lithography and EDA interactions needed to enable manufacturing and design with high-NA EUV processes and mask stitching.

Presenting Author

Michael performed his graduate studies in computational lithography at UC Berkeley where he focused on fast 3D mask modeling projects, including buried defect simulations of EUV mask blanks. He spent two summers studying phase defect printability as an intern at Intel, as well as one summer co-founding CommandCAD, a DFM startup working on image-based 2D design rule checking that was eventually acquired by Cadence. He received his PhD in Applied Science and Technology from UC Berkeley in 2005 before joining Mentor Graphics as a modeling software engineer. Over 17 years at Mentor, Michael was involved in all aspects of computational lithography modeling, ending his time as Director of Modeling, SMO, ILT, and GPU Simulation. He joined Synopsys in May of last year as Sr. Director of R&D for Computational Lithography Modeling.

P31

Development of High-Brightness Xe LPP Source and its Applications (Invited)

Dong Gun Lee and Byung Gook Kim

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45, Dongtansandan 10-gil, Hwaseong-si, Gyeonggi-do, Republic of Korea

LPP EUV sources using Xe jets as targets have the advantage of producing less debris and having a relatively simple system. However, they have a drawback: they cannot create spatially localized plasma due to the effect of gas spreading in a vacuum. On the other hand, LPP sources using solidified Xe targets can reduce the size of the plasma to the scale of the laser focus point, increasing brightness and efficiency in converting to EUV light. But this also increases the cost of building and operating the entire EUV source system because it requires an additional cryogenic system. In this development, we have created a localized high-density Xe target using an advanced shocked nozzle instead of the traditional gas jet nozzle. By focusing a laser on this target, we have developed a high-brightness EUV source. We introduce this technology and present examples of its application in a spectra photometry system. An actinic system that utilizes such a high-brightness and clean EUV source is expected to have high industrial applicability due to its low equipment cost and reduced maintenance expenses.

Presenting Author

Dong Gun Lee, CTO of ESOL, holds M.S. and Ph.D. degrees in Physics from KAIST, where he focused on EUV source development during his graduate studies. With 16 years of experience as a Senior Principal Engineer at Samsung Electronics, he has expertise in EUV(actinic) tools and mask fabrication process development .

P32

Modeling a Discharge-Produced Plasma (DPP) EUV Source (Invited)

David Reisman[1], Daniel Arcaro[1], Fred Niell[2]

[1]Energetiq Technology, Inc., Wilmington, MA 01887, USA
[2]Nielltronix Inc., Tampa, FL 33609, USA

We have recently developed an improved discharged-produced plasma (DPP) EUV source. The source uses a xenon plasma in a Z-pinch configuration to produce 13.5 nm (±1% BW) radiation. Based on the successful Energetiq Electrodeless Z-Pinch™ design, the new source uses an innovative transistor-based switching system to overcome the limitations of traditional magnetically switched systems. With this configuration, which allows an increase in both pulse frequency and energy-per-pulse, we have doubled our EUV power output. Critical to the development process was the use of radiation-magnetohydrodynamic (RMHD) simulations. We will detail how simulations were used to optimize the design by providing insight into the xenon plasma pre-ionization and Z-pinch stages. We will also discuss the important role of opacity data in the RMHD calculations. Finally, we will present calculations of a potential Blue-X (6.7 nm) source using a neon Z-pinch.

Presenting Author

David Reisman is a consultant 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).

P33

Compact Radiation Sources from Laser-Plasma Accelerators at LBNL's BELLA Center (Invited)

Jeroen van Tilborg

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

X-ray sources, including coherent free electron lasers at energies up to keVs, and incoherent monoenergetic Compton scattering sources at MeV energies and beyond, have revolutionized a broad range of science and field applications ranging from high-energy density physics, advanced manufacturing, imaging of complex structures, and use in medical and security contexts. Such sources require electron accelerators at GeV levels, and technologies to make such accelerators smaller have the potential to both greatly broaden the science accessible and enabling field applications. Ultrashort laser pulses enable resonant excitation of plasma waves, efficiently driving structures that can accelerate electrons at rates of in the range of a GeV per centimeter. These compact electron beams are then used to develop novel compact photon sources including free electron lasers, X-ray betatron sources, and MeV photons from laser scattering. Work on such light sources at the BELLA Center at LBNL will be highlighted.

This work was supported by the U.S. DOE National Nuclear Security Administration Defense Nuclear Nonproliferation R&D (NA-22), by the Office of Science of High Energy Physics (HEP) and Basic Energy Sciences (BES) under Contract No. DE-AC02-05CH11231, and through a collaborative grant from TAU Systems Inc.

Presenting Author: Jeroen van Tilborg

Jeroen van Tilborg is a scientist at the Lawrence Berkeley National Laboratory (LBNL), and Deputy Director at the LBNL's BELLA Center. He received his PhD degree in Applied Physics from the Eindhoven University of Technology in the Netherlands in 2006, and has been active experimentally at LBNL since 2001. His current research interests include plasma physics, high-peak-power laser science, and laser-plasma accelerator physics including its compact light source applications.

Laser-plasma Acceleration: Next Generation X-ray Light Sources for Industrial Applications (Invited)

Félicie Albert

Director, Jupiter Laser Facility
Lawrence Livermore National Laboratory

One of the most prominent applications of modern particle accelerators is the generation of radiation. For example, in a synchrotron or an x-ray free electron laser (X-FEL), high energy electrons oscillating in periodic magnetic structures emit bright x-rays.

Despite their scientific appeal that will remain evident for many decades, one limitation of synchrotrons and X-FELs is their typical mile-long size and their cost, which often limits access to the broader scientific community.This talk will review the prospects of using plasmas produced by intense lasers as particle accelerators and x-ray light sources, as well as some of the applications they enable. Experiments conducted at facilities of LaserNetUS, a network of high intensity lasers in North America, will also be discussed.

A plasma is an ionized medium that can sustain electrical fields many orders of magnitude higher than that in conventional radiofrequency accelerator structures. When short, intense laser pulses are focused into a gas, it produces electron plasma waves in which electrons can be trapped and accelerated to GeV energies. This process, laser-wakefield acceleration (LWFA), is analogous to a surfer being propelled by an ocean wave. Many radiation sources, from THz to gamma-rays, can be produced by these relativistic electrons. Betatron x-ray radiation, for example, is produced when relativistic electrons oscillate during the LWFA process. This presentation will also review several LWFA-driven sources in the keV-MeV photon energy range, including X-FELs, Compton Scattering, and bremsstrahlung sources. An important use of x-rays from laser plasma accelerators we will finally discuss is their emerging applications, in High Energy Density (HED) science, fusion energy, nondestructive evaluation and potential other industrial applications.

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Presenting Author

P35

Tm:YLF lasers for driving EUV Sources

Zbynek Hubka*, Issa Tamer, Leily Kiani, Jason Owens, Andrew Church, František Batysta, Tom Galvin, Drew Willard, Andrew Yandow, Alex Chemali, Justin Galbraith, Emily Sistrunk, Robert Plummer, Brendan A. Reagan, and Thomas M. Spinka

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EUV lithography, driven by CO2 lasers and utilizing Sn laser-produced plasmas, entered high volume manufacturing for critical layers in 2019, heightening the demand for higher power EUV sources with improved overall efficiency. The Big Aperture Thulium (BAT) laser concept, initially created by LLNL for compact laser-driven particle accelerators, offers a promising solution due to the versatility of this system. It's based on directly diode pumped Tm:YLF active medium and operates at a wavelength of around 2 µm, where the conversion efficiency of generating in-band EUV radiation is comparable to CO2 lasers [1], and with wall-plug efficiency approaching 20 % [2]. We will showcase achievements in generating pulses with >100 J and >20 J pulse energies within millisecond and nanosecond-duration pulses, respectively [3], high peak power operation results, and the latest development in shot-on-demand 1 kHz burst mode operation. Additionally, we will show results from our helium gas-cooled Tm:YLF experiment, surpassing state-of-the-art heat removal rates for high peak power laser architectures by almost 10 times, exceeding 20 W/cm^2 [4].

This work was performed by LLNL under Contract DE-AC52-07NA27344, and was supported by the LLNL-LDRD program under Projects 20-ERD-006 and 21-ERD-016, and by the DOE SC ARDAP Accelerator Stewardship Program under Project SCW1648.

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[4] Z. Hubka, et al., "Development of high peak and average power Tm:YLF lasers," Proc. SPIE 12864, 1286402 (2024).

Presenting Author

Zbynek, initially a fusion enthusiast, switched to lasers during his postgraduate studies at Czech Technical University in Prague, Czech Republic. He then earned his PhD while developing thin-disk based pump lasers for the 1 kHz OPCPA system at ELI Beamlines. After a brief stint at the HiLASE laser center, fusion fate pleasantly intervened – he found himself as a postdoc at LLNL, NIF & Photon Science, just a month before the historic ignition milestone in 2022. Currently, as part of the Advanced Photon Technologies group, he works with Issa Tamer and Brendan Reagan on Tm:YLF-based high-peak and high-average power laser systems.

P36

Commercializing Laser-Wakefield Accelerator Systems and Their Applications (Invited)

Stephen V. Milton

TAU Systems Inc., Austin Texas

The laser-wakefield accelerator (LWFA) has grown from a purely research and development device found in many laboratories around the world to a mature technology ready to be transitioned to the commercial sector and used for real-world applications. At TAU Systems, we are doing just that, commercializing the LWFA so that it may be applied to a wide variety of applications. In this talk I will provide historical background about LWFAs including their present state of maturity, and then I will talk about TAU's progress in producing and commercially fielding rep-rated LWFA systems to be used for a number of applications including those requiring high-brightness (peak and average) EUV beams.

Presenting Author

Stephen is a recognized international leader in the areas of free-electron lasers and accelerator science, engineering, and technology and is Tau's Vice President for Accelerator Science. He has designed, overseen the construction, commissioned, and overseen operations of a wide variety of accelerators and free-electron lasers systems around the world and is credited for or has been a part of a number of world firsts in the field of free-electron lasers. Stephen received his BS in physics from the University of California, Davis, and an MS and PhD in physics from Cornell University. He is a fellow of both the American Physical Society (APS) and the Institute for Electrical and Electronics Engineers (IEEE) as well as the recipient of the IEEE award in particle accelerator science and technology.

P37

Nanoscale Coherent Imaging and Functional Characterization using Tabletop-Scale Coherent EUV Sources (Invited)

Henry C. Kapteyn and Margaret M. Murnane

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Next-generation nano and quantum systems and devices are becoming increasingly complex, with their behavior governed by interface quality or precise chemical, interfacial or dopant composition. Furthermore, characterizing their functional as well as structural properties is becoming increasingly challenging as these structures shrink, requiring new capabilities and techniques.

Tabletop-scale EUV light sources based on high-order harmonic generation provide a unique capability for probing the nanoworld in novel ways. The high harmonic process makes use of attosecond time-scale quantum dynamics to coherently upconvert laser light to short wavelengths ranging from the deep-UV to keV soft x-rays. The coherence of the upconversion allows for unparalleled control over the spectral, temporal, and polarization properties as well as the orbital angular momentum of the emitted x-ray beam. This provides a powerful new tool, for example for diffraction-limited coherent x-ray imaging, for coherently manipulating quantum materials using light, and for extracting functional thermal transport, electronic, magnetic and mechanical properties using time resolved measurements.

Project is funded by: NSF DMR-1548924 and DOE DE-FG02-99ER14982

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Presenting Author

Henry C. Kapteyn is CTO of Kapteyn-Murnane Laboratories Inc. (KMLabs), a Professor of Physics and ECE at the University of Colorado at Boulder, and a fellow of JILA—a research institute joint between the University of Colorado and NIST. He and his wife and long-term collaborator, Margaret Murnane, are well known for their research in femtosecond lasers, and for understanding how to coherently upconvert this light to make a “tabletop x-ray laser” that generates ultrashort bursts of short-wavelength light. In recent years, they have applied this source to pioneering studies of atomic, molecular, and material studies at short length- and time-scales. He has published several hundred papers in topics ranging from laser science and engineering to materials to nanoimaging. He was elected to the

US National Academy of Sciences in 2013, the American Academy of Arts and Sciences in 2018, and is a fellow of the American Physical Society, the Optical Society of America, and the American Association for the Advancement of Science. His awards include the Adolph Lomb Medal of the OSA in 1993, the Ahmed Zewail Award of the ACS in 2009, the R.W. Wood Prize of the OSA in 2010, the Arthur Schawlow Prize of the APS in 2010, and the Willis Lamb Award in Quantum Electronics in 2012, and the 2021 Benjamin Franklin Medal in Physics.

P38

The Recent Process on Steady-State Microbunching EUV Light Source Project

Zhilong Pan, Xiujie Deng, Wenhui Huang, Renkai Li, Alexander Chao,
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Steady state microbunching (SSMB) proposed by Alexander Chao and Daniel Ratner is a new concept of accelerator light source, which means to maintain the microbunching in storage rings for coherent radiation production. By combining the high coherence and high repetition rate, SSMB can provide very high average power radiation. And the radiation wavelength can cover THz to soft X-ray.

To promote the SSMB physics research and develop a SSMB-EUV light source, a taskforce has been established in Tsinghua University since 2017. Recently, we are continuing the proof of principle experiment and have observed multi-turn coherent radiation by modulating the electron bunch with laser single-turn on MLS storage ring. The experiment results are in very good agreement with theoretical prediction, which proof this kind of mechanism (maintain micro-bunch in storage ring) can work well.

We have also proposed a complete design for high average power EUV radiation based on SSMB. The proposal will provide kW EUV average power at the radiation wavelength of 13.5 nm within 2% bandwidth. We have done the start to end study for this proposal and the researches on the key technologies are also underway. This kind of EUV light source may open a new roadmap to meet the requirements of EUV lithography

Presenting Author

Zhilong Pan is an accelerator physicist at Tsinghua University, Beijing, China, as an assistant researcher. He received his B.S. degree From Department of Engineering Physics, Tsinghua University in 2015, and continued his Ph.D. study at Tsinghua University. He received his Ph.D. degree in 2020, and continuing his research as a postdoc at Tsinghua University between 2020 to 2023. His work focus on storage ring design, nonlinear optimization, IBS study, physics of steady-state microbunching (SSMB).

P39

Energetiq Source Update: Spherically Shaped Source for High NA Metrology

Kosuke Saito[1], David Reisman[2], Daniel Arcaro[2], Michael Roderick[2]

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In recent years, there has been a shift toward high numerical aperture (NA) in semiconductor metrology where a smaller source size is preferable. Energetiq's Electrodeless Z-Pinch™ extreme ultraviolet (EUV) light sources [1] create light in the key 13.5 nm region used for various semiconductor metrology applications. This electrodeless technology relies on an inductively driven plasma loop to produce a plasma current with a rod-like shape rather than a spherical shape. As the source design was further developed from its original 10W output to its current 20W output, the plasma shape did not drastically change. In this poster, we will present data investigating whether Energetiq's source can provide a spherically shaped plasma current to support high-NA metrology. We will also show updates to our EUV development facility established at Hamamatsu Photonics K.K. in Japan.

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Presenter

Daniel Arcaro is Sr. Scientist Plasma Physics at Energetiq Technology, Inc.

P40

EUV and Soft-X-Ray Photonic Integrated Circuits (XPICs) - Overview and First Results at 13.5 nm

Robert Riedel[1], Philipp Merkl[1], Jan Heye Buss[1], Bastian Manschwetus[1], Valentina Shumakova[1], Rebeca Martinez Vazquez[2], Caterina Vozzi[2], Anna G. Ciriolo[2] and Monica Bollani[2], Aldo Frezzotti[3] and Salvatore Stagira[3], Valer Tosa[4]

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Integrated photonic devices in the extreme ultraviolet (EUV) and soft-X-ray range (XPICs) are a radically new field of research with relevant applications in EUV lithography. We present the fabrication of waveguides and microfluidic devices to generate and manipulate high-brilliance EUV light on-a-chip, thus bringing meter-long set-ups down to centimeter-sized integrated devices. Our work represents a paradigm shift through the synergetic interaction among different disciplines, such as ultrafast lasers, advanced nonlinear optical technologies, femtosecond laser micromachining, fluid dynamics, nanotechnology, and EUV to soft X-rays technology.

The presentation will provide an overview about the field as well as insights about the XPIC design and fabrication process. Further, we will show first results of 13.5 nm EUV laser light generation via high-harmonic generation (HHG), coupling an ultrafast laser to a microfluidic waveguide chip. Further, we will demonstrate first examples of actual functional XPIC devices, such as optical filters. We will also discuss future integrated devices, for example an EUV interferometer-on-a-chip suitable for hyperspectral imaging with nanometer resolution for advanced mask and wafer inspection.

Presenting Author

Robert Riedel graduated in 2010 from Friedrich-Schiller-University Jena in Physics with focus on photonic integrated circuits and femtosecond laser micromachining (Institute of Applied Physics). He received his PhD in 2013 at the University of Hamburg for his work at DESY, developing high-power femtosecond Lasers and EUV/soft- Xray sources and metrology tools. While continuing his work at DESY from 2013 2015, he founded Class 5 Photonics with colleagues working in Hamburg, Germany and Stanford, USA. Together with his team, he received several innovation awards.

P41

Enhanced EUV Lighting with Focusing Electrode Adapted C-beam Irradiation Technique

Iksu Kim, Kyu Chang Park[1]

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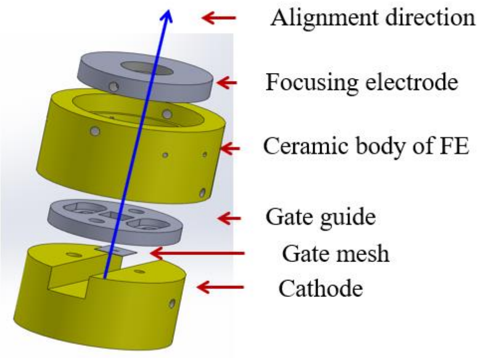
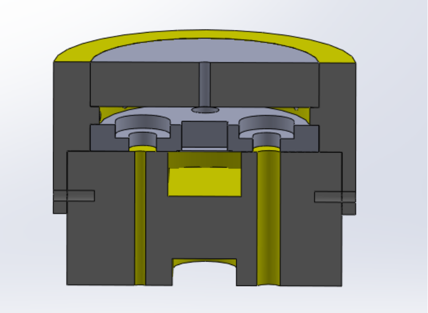
EUV (Extreme Ultraviolet system) using LPP (Laser produce plasma) and DPP (Discharge produce plasma) method is commonly used in high volume semiconductor manufacturing. However, conventional method in EUV system has several problems with debris and cost. We develop our own EUV irradiation technology by C-beam (Cold Cathode beam) try to solve EUV irradiation problems. We have solved debris and cost issues by our C-beam irradiation technique. However, we found that EUV intensity was relatively low. So, we are trying to investigate focuser electrode effect with our EUV irradiation.

In this study, we will discuss about the effect of beam spot for the EUV generation in the anode by using focusing electrode. By applying the focuser, electron beam spot size decrease. It means that current density will be higher because of the spot size decreasing. Current density of our beam is related to the EUV photo current that measure by EUV photodiode. We will use the sapphire as a PL (Photo Luminescence) detector that can measure the gray value and FWHM (Full wave half maximum) of EUV irradiation by C-beam.

C-beam (cold cathode beam) is fabricated on silicon wafer by photolithography. First sputtering Nickel on the wafer. And after that we coat PR on the wafer. Next step is exposure. By using 1-island mask we pattern the sample and then develop the PR. Remained Nickel is etched by etchant and grow the CNT (Carbon Nano Tube) by PECVD (Plasma Enhanced Chemical Vapor Deposition) technique. And I-V characteristics measure with diode and triode configuration. Finally, we evaluated photo-current with various exposure condition and focusing electrode biasing conditions.





Cross section of module

Presenting Author

Mr. Iksu Kim has his BS in the Information of Display from Kyung Hee university. He is currently an Integrated Ph. D student in the Department of information display in Kyung Hee university, Seoul 02447, South Korea.

P42

Testing Platform of Extreme-ultraviolet (EUV) Materials and Optical Components

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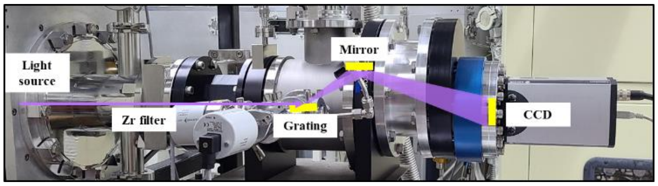
During the past years, multi-patterning techniques such as litho-etch-litho-etch (LELE) have been used to print tight-pitch resist patterns for advanced devices. However, there are limitations of high cost and shrinkage restriction of channel length. Therefore, EUV lithography was introduced to overcome the limitations and is considered a core technology for next-generation semiconductor processing [1]. To transfer the fine patterns, research on EUV components, such as photoresists, pellicles, and mirrors, has been actively conducted but it is difficult to verify performance quantitively. Therefore, we suggest the testing platform for EUV components, consisting of an EUV source, an optical system, and a spectrometer as shown in Fig. 1.

We focus on the characterization of the EUV source. The EUV light is generated from a z-pinch plasma source and its spectrum is calibrated by the spectrometer. The parameter optimization is conducted to obtain enough optical power with a wavelength of 13.5 nm. As a result, it reaches 30 mJ/cm^2, corresponding to 30 mJ/cm^2 in terms of exposure dose.

In conclusion, we characterized the EUV source and optimized the source parameters. Because the resultant optical power is enough to print patterns, this system can be utilized to verify the newly developed photoresist.



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

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P43

High-average-power EUV FEL for Lithography (Invited)

Dinh Nguyen, Chris Anderson, David Douglas, Bruce Dunham, William Lou,
Christopher Mayes, George Neil, and Gennady Stupakov

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We present a unique EUV free-electron laser (FEL) design and architecture that meets the specific requirements of high-volume leading-edge semiconductor manufacturing. The tunable EUV FEL output has a narrow spectral bandwidth well within the reflectivity curve of multilayer MoSi mirrors, while the high-repetition-rate femtosecond EUV pulses enable mitigating the laser beam's coherence effects. The overall machine footprint of the FEL capable of supporting multiple EUV lithography steppers is on the scale of a utility facility. We will also address the source availability concerns with availability data from a previous ERL FEL and by utilizing redundancies of critical hardware.

Presenting Author

P51

Dry Resist Patterning Readiness Towards High NA EUV Lithography (Invited)

Anuja De Silva[a], Ali Haider[a], Ching-Chung Huang[a], Mohand Brouri[a],
Francesco Gullo[a], Shruti Jambaldinni[a], Zhengtao Chen[a], Benjamin Kam[a],
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Dry resist deposition and development technology is being introduced to break the tradeoffs among resolution, sensitivity, roughness, and defect performance to enable HVM for high NA EUV with its full productivity entitlement. An all EUV dry resist technology offers differentiating process knobs that can enhance performance compared to conventional EUV resists. In this talk, we demonstrate the progress of dry resist development to address specific challenges of high NA EUV lithography. As features scale, resist thickness and interface between resist and underlayer play a crucial role. The co-optimization of underlayers with dry technology enables tuning of the patterning stack for optimal performance. Dry deposition of resists offers precise, recipe adjustable control over thickness and composition to improve material variability. Dry development eliminates the capillary forces which lead to pattern collapse and enhances the ability to print features at higher aspect ratio. Dry resist patterning performance at pitch 24nm dense line-space and pitch 32nm hexagonal dense pillars and contact holes will be presented showing the readiness towards the high NA EUV patterning. The ability of dry resist patterning to resolve small tip-to-tip structures with lower variability demonstrates the possibility of reducing the mask numbers with high NA EUV. Superior performance of dry resist has been validated through electrical readout with test vehicles available at most aggressive pitches available (at pitches 28/26nm L/S) on current 0.33NA scanner. The need to scale the patterning stack to enable pattern transfer with low defectivity in the sub pitch 24nm regime will also be discussed.

Presenting Author

Anuja De Silva is a semiconductor technologist and associate editor at SPIE.

P52

Probing Chemical Transformations in EUV Resists

Oleg Kostko

Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

In EUV lithography, only a fraction of EUV photons is absorbed by a resist film, with the rest being absorbed by the substrate or underlayer. This leads to the emission of photoelectrons and possibly Auger electrons. These primary electrons can generate slower secondary electrons, crucial for pattern formation in EUV photoresists. In chemically amplified photoresists, slow electrons attach to photoacid generator molecules, leading to polymer solubility changes. Metal-oxide resists have a different mechanism, where EUV photons or electrons cleave organic ligands, leading to metal-oxide cluster condensation. Understanding electron-resist interactions is essential for optimizing EUV lithography resolution.

Utilizing electron spectroscopy techniques, we discovered that EUV exposure of resists affects the electron emission spectra, primarily impacting the emission of slow secondary electrons. Through this method applied to resist components, we begin to decipher the role of resist components in electron generation, capture, and transmission. We employ similar approaches to evaluate chemical transformations in photoresists during EUV exposure. Additionally, we investigate electron-induced chemistry in photoresist materials by exposing thin films of model resists to an electron beam. Changes are analyzed through outgassing, film thickness loss, and FTIR spectroscopy. Electron energies ranging from 20 to 80 eV are employed to assess the effects of both fast primary and slow secondary electrons on photoresists.

Presenting Author

Oleg Kostko obtained his doctoral degree from the University of Freiburg, Germany, in 2007. In the same year, he joined the Berkeley Lab as a postdoctoral fellow. After a brief stay at SRI International, where he studied atmospherically relevant processes, he returned to the Berkeley Lab to lead an effort in developing novel soft X-ray spectroscopies on nanoscale systems. As part of the Center for X-Ray Optics at Berkeley Lab, he pioneers the development of novel electron spectroscopies specifically to probe EUV materials, focusing on the direct characterization of the role of low-energy electrons in EUV patterning processes.

P53

Advanced Processes for High-NA EUV Lithography (Invited)

Cong Que Dinh

Tokyo Electron Kyushu Ltd., Japan

High-NA EUV lithography will require low roughness and defect levels, due to small feature sizes and expected high levels of integration. To achieve these requirements while avoiding large losses of productivity, it is necessary to break the dose-roughness and dose-defect trade-off relationships. In this paper, we will show how advanced processes can fulfil the requirements.

Presenting Author

Dr. Dinh is a lithography senior specialist at Advanced Technology Department in Tokyo Electron Kyushu. He is now 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.

P54

EUV Interference Lithography towards the Ultimate Resolution of Photon-based Nanopatterning

Iason Giannopoulos

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Extreme ultraviolet (EUV) lithography stands at the forefront as a pivotal nanopatterning technique in mass production of semiconductor chips. EUV interference lithography (EUV-IL) plays a crucial role in photoresist development and in various scientific projects involving nanopatterning. At the Paul Scherrer Institute, we have developed an EUV-IL setup utilizing synchrotron radiation that provides spatially coherent and polarized EUV light. These systems employ two or more transmission diffraction gratings on thin silicon nitride membranes. EUV light diffracts through the gratings, creating an interference pattern on the photoresist, typically line/space patterns or square/hexagonal arrays of holes, kagome patterns etc. Despite efforts to develop high-resolution and efficient gratings towards single-digit nanolithography, significant challenges emerge at the sub-10 nm regime, hindering the pursuit of ultimate resolution. To this end, we introduced mirror interference lithography (MIL) that uses reflected light to overcome the grating-induced obstacles. In this setup, two mirrors create an interference pattern with a pitch dependent on grazing angle. We achieved resolutions down to 5 nm HP, setting a new record in nanolithography resolution. This method proves invaluable for testing photoresists and pattern transfer techniques for high-/hyper-NA EUV lithography, as well as for high-resolution nanostructures for scientific exploration.

Presenting Author

Dr. Giannopoulos is a postdoctoral researcher at the Laboratory for X-ray Nanoscience and Technologies, Paul Scherrer Institute, Switzerland. He specializes in the development, fabrication, and characterization of novel micro/nanoscale devices. He holds two M.Sc. degrees, one in micro- & nanosystems from the Swiss Federal Institute of Technology (ETH Zurich), Switzerland, and another in applied mathematics and physical sciences from the National Technical University (NTUA) of Athens, Greece. In 2021, he got his Ph.D. in electrical engineering and information technology from ETH Zurich for research on non-von Neumann computing conducted at IBM Research Zurich, Switzerland.

Multi-Trigger Resist Patterning towards High–NA EUV Lithography (Invited)

C. Popescu[a], G. O'Callaghan[a], A. McClelland[a], C. Storey[a], J. Roth[b], E. Jackson[b], A.P.G. Robinson[a,c]

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High-NA EUV lithography will enable the introduction of the next semiconductor nodes but novel resist materials will be required to support its use. More stringent resolution, roughness and dose requirements are hampered by a decreased depth of focus, which will affect both the resist and the underlayer and stack if pattern transfer is to be maintained. Irresistible Materials (IM) is developing novel resists based on the multi-trigger concept. The current resist platform is a negative tone, PFAS-free material capable of patterning at high resolution and low dose at film thicknesses at 22nm and below. In a multi-trigger resist (MTR) multiple elements must be simultaneously activated to enable a catalytic reaction. Chemical contrast and resolution are enhanced due to a dose dependent intrinsic quenching behavior.

MTR shows good lithographic results and wide flexibility. MTR Gen1 introduced tuneable absorbance as high as 18µm-1. MTR Gen2 has improved three areas of the fundamental chemistry, namely increased monomer activation rate, optimised ring opening polymerisation reactions and improved selectivity of chain termination. This has allowed p28 line/space patterning at 56mJ/cm^2 using a 21.5nm film thickness, with an unbiased LER of 2.2nm, and p32 hexagonal pillars patterning at 76mJ/cm^2 using a 20nm film thickness, with an unbiased LCDU of 2.6nm. Here we present the continuing evolution of the MTR system, discussing recent patterning of p32 contact holes using 20-30nm film thickness, and investigating sub 50mJ/cm^2 patterning for both pillars and holes.

Presenting Author

Alex Robinson is co-founder, and Chief Technical Officer of Irresistible Materials Ltd, which is developing materials to support EUV lithography, and Professor of Nanoengineering at the University of Birmingham in the UK. He also co-founded the fluorescent materials company Chromatwist Ltd.

P56

Enhancement of Photosensitivity and Stability of Sn-12 EUV Resist by Integrating Photoactive Nitrate Anion

Yeo Kyung Kang[a], Chan-Cuk Hwang[b], Myung-Gil Kim[a]

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The semiconductor industry is moving towards using advanced extreme-ultraviolet lithography (EUVL) to tackle the limitations of traditional photolithography in microprocessor and memory chip integration, leading to increased research on new inorganic EUV photoresists. However, challenges such as low EUV sensitivity, limited photochemistry knowledge, and stability issues have arisen. In this study, the EUV sensitivity and stability of tin oxo clusters are enhanced by combining them with photoactive nitrate anions, creating a compound $[(BuSn)_{12}O_{14}(OH)_6](NO_3)_2$ (TinNO3). The TinNO3 demonstrates low photosensitivity (32 mJ/cm²) and maintains stability in various post-exposure environments. TinNO3 also shows enhanced resistance to dry etching, allowing for selective etching of silicon and amorphous carbon layers. By optimizing post-exposure bake parameters, photoresist-substrate adhesion, and development conditions, the study successfully produced well-defined CD 45 nm L/S patterns on TinNO3 thin films using ArF lithography.

[1] *Appl. Surf. Sci.* **2024**, *656*, 159564

Presenting Author

Dr. Myung-Gil Kim is an Associate Professor in the School of Advanced Materials Science & Engineering at Sungkyunkwan University. He received his B.S. in Chemistry from KAIST (South Korea, 2006) and Ph.D. in Chemistry from Northwestern University (USA, 2012). He worked as a Post Doc. researcher at Stanford University (USA) until 2014. Dr. Kim worked as faculty member at Dept. of Chemistry, Chung-Ang University (2014-2019).

Dr. Kim published more than 110 SCI research articles in high impact journals including Nature Materials, Nature Electronics, Nature Communication, Science Advances, Proceedings of the National Academy of Science of the U.S.A., Advanced Materials, JACS, etc. His current research interests include the development of solution based synthesis of inorganic materials and hybrid materials for novel semiconductor and advanced lithography.

P57

EUV Lithography Using Zeolitic Imidazolate Frameworks

Michael Tsapatsis

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Metal-organic frameworks (MOFs) hold promise for applications including gas separation, sensing, energy conversion and catalysis due to their tunable properties enabled by the structural diversity stemming from the plethora of available metal/organic linker combinations.[1] MOFs can also function as high sensitivity resists in extreme-ultraviolet (EUV) lithography based on the high absorption cross-section of certain metals.[2] Zeolitic imidazolate frameworks (ZIFs),[1] a class of MOFs, which have been proposed for EUV lithography based on spin-on to solvent-free deposition and development methods[3-7] will be discussed.

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Presenting Author

Michael Tsapatsis (https://tsapatsislab.wse.jhu.edu/) is a Bloomberg Distinguished Professor at Johns Hopkins University (JHU). Before joining JHU (2018) he was a faculty at the University of Minnesota (2003-2018) and the University of Massachusetts Amherst (1994-2003). He received an Engineering Diploma (1988) from The University of Patras, Greece, and MS (1991) and Ph.D. (1994) degrees from Caltech. He has supervised/co-supervised to completion the Ph.D. thesis of ~50 graduate students and advised ~40 former postdoctoral fellows, who now work in the chemical and microelectronics industries, in national laboratories, and in academia. In 2015, he was elected to the National Academy of Engineering for his contributions to porous materials for catalysis and separations.

P58

Hybrid Multilayer EUV Dry Resist for 1.5 nm Technology Node

Myung Mo Sung

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Basic requirements for good patterns using extreme ultraviolet lithography (EUVL) are sensitivity, resolution, line edge roughness (LER), outgassing, etch resistance, defect density, and reproducibility. Among them, it has been proved that resolution, LER, and sensitivity (RLS) are interdependent with each other. The trade-off between RLS pose a critical challenge in the race towards device downscaling to 1 nm node. LER is the most important consideration to determine the manner in which EUVL will be employed. Recently, we develop a new EUV dry resist with organic-inorganic hybrid multilayer structures vertically tailored with several functional layers by using molecular layer deposition. Additionally, each layer includes a self-assembled organic monolayer to generate a vertical molecular wire structure. The hybrid multilayer resist shows high EUV sensitivity from the high EUV absorbing and reactive layers there. Furthermore, the vertical molecular wire structure of the hybrid resist generates exceptionally low LER.

Presenting Author

Prof. Myung Mo Sung is a Professor of Chemistry and head of the Organic-Inorganic Hybrid Thin Film Laboratory at Hanyang University. He received his B.S. in Chemistry at Seoul National University and Ph.D. in Chemistry from the University of Houston in 1996. And he had been a postdoctoral fellow in Department of Chemical Engineering at the University of California, Berkeley. His research focuses on functional inorganic nanolayers as well as organic-inorganic hybrid thin films by molecular-atomic layer deposition for various electronic and optoelectronic device applications. He has authored or co-authored more than 160 peer-reviewed publications in highly reputable journals, including *Nature Nanotechnology*, *Advanced Materials, Nano Letters, Angewandte Chemie, J. Am. Chem. Soc*

P59

DOE Accelerate Initiative Project for Accelerating Next-Generation EUV Photoresist Development (Invited)

Chang-Yong Nam[1]

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In this talk, I will provide an overview of the DOE Accelerate Initiate project entitled "Angstrom Era Semiconductor Patterning Material Development Accelerator", an \$8M project aiming to accelerate the development of next-generation EUV photoresists via vapor-phase materials synthesis and machine learning correlation between proxy variables and EUV patterning performance. I will also briefly discuss the construction of an interference EUVL patterning end-station being pursued at the National Synchrotron Light Source II (NSLS-II) of Brookhaven National Laboratory under the collaboration with the Paul Scherrer Institute at Swiss Light Source. This is a part of Brookhaven's efforts to create science infrastructure that can support the High NA EUVL Center at the Albany NanoTech whose establishment was announced recently as a part of \$10B partnership between New York State and semiconductor industry.

Presenting Author

Chang-Yong Nam is a Scientist at the Center for Functional Nanomaterials of Brookhaven National Laboratory (BNL), and an Adjunct Professor at Stony Brook University and the University of Texas at Dallas. He is currently a Lead PI of the DOE Accelerate Initiative project aimed at accelerating the development of EUV photoresist development. 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 two primary areas: (a) Development of atomic layer deposition (ALD) methods towards microelectronics and energy applications; (b) Materials processing and device physics in low dimensional semiconductors. His awards include DOE Accelerate Initiative Award (2023), Battelle Inventor of the Year (2022), Winner of DOE National Labs Accelerator Pitch Event (2021), and Goldhaber Distinguished Fellowship (2007)

P60

Sequence Control in Polypeptoid Photoresists and Its Effects on Patterning Performance (Invited)

Christopher K. Ober, Chenyun Yuan, Rachel Wang

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The next generation of microelectronics will depend on photoresists working at EUV wavelength (13 nm) yet the role of stochastics (chemical heterogeneity) remains poorly understood. New concepts in photoresists are needed to form high resolution, high image-fidelity patterns while operating under demanding exposure conditions. Here we report on controlled sequence polypeptoid photoresists with their ability to make chemically identical polymer chains [1]. The level of molecular control is superior to other polymer resists with not only molecular size, but composition and even chemical sequence being identical. We are exploring them as a model system to understand the role of chemical stochastics on resist performance. Sequence-controlled resists derived from polypeptoids are studied and explore chain sequence control and placement of functional moieties in the polymer on resist performance [2]. Examples of working peptoid resists, a discussion of patterning performance under UV, e-beam and EUV exposures, and resulting unexpected observations will be presented.

[1] Florian Käfer, Chaoqiuyu Wang, Yuming Huang, Francesca Bard, Rachel Segalman, Christopher K. Ober, "Polypeptoids, exploring the power of sequence control in a photoresist for extreme-ultraviolet lithography", Advanced Materials Technologies, in press; 10.1002/ADMT202301104

[2] Florian Kaefer, Chenyun Yuan, Cameron Adams, Rachel Segalman and Christopher K. Ober, "Photoresist Design to Address Stochastics Issues in EUV Resists", J. Photopolym. Sci. Tech., 36(1), 61-66 (2023).

Presenting Author

Christopher Kemper Ober is the Francis Bard Professor of Materials Engineering at Cornell University. He received his B.Sc. (Honours Chemistry) from the University of Waterloo, Canada and his PhD in Polymer Science & Engineering at UMass Amherst. Ober was elected to the National Academy of Engineering in 2023 and the Canadian Academy of Engineering in 2024 in part for his work on photolithography. He is the 2006 winner of the ACS Award in Applied Polymer Science and received a Humboldt Research Prize in 2007. In 2009, Ober was named a Fellow of the ACS and was awarded the Gutenberg Research Prize by the University of Mainz. He was elected a fellow of the APS (2014), the AAAS (2015) and made a SPIE Senior Member (2018).

Tetrahydroxy-tetramethyl-cyclotetrasiloxane as an Inorganic EUV Resist: Exploring Cross-Linking Mechanisms and Lithography Performance

Jiyoung Bang,[a] Hyeok Yun,[a] Wonchul Kee,[a] Siwoo Noh,[b] Ki-Jeong Kim,[b]
Sunyoung Lee,[c] and Hyun-Dam Jeong[a,*]

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37673, Republic of Korea
[c]*Sungkyunkwan University ,Suwon, Gyeonggi-do, 16419, Republic of Korea*

In the landscape of Extreme Ultraviolet Lithography (EUVL), inorganic resist materials have garnered attention for their excellent mechanical durability and resistance to dry etching processes. Embracing this paradigm, we are utilized tetrahydroxy-tetramethyl-cyclotetrasiloxane (tetraol) as an EUV resist material. Tetraol stands out with its impressive etch resistance, surpassing bottom anti-reflective coating (BARC) by 1.7 times and spin-on-carbon (SOC) by an astounding 65.4 times.With an electron beam sensitivity (D_{50}) of 21.9 μC/cm^{-1} and an EUV absorption coefficient of 9.89 cm^{-1}, tetraol demonstrates the capability to precisely form photoresist patterns in EUVL, achieving a 22 nm HP pattern at 55 mJ/cm^{2}. In-depth investigation into the electron beam crosslinking mechanism of tetraol has uncovered fascinating insights through our analysis, employing techniques such as FT-IR, TOF-SIMS, and XPS. Remarkably, tetraol's four hydroxy groups emerge as pivotal contributors to its sensitivity. These groups efficiently form network siloxane bonds via electron beams and thermal energy, facilitating the transformation of tetraol into a negative-tone photoresist. Additionally, the presence of hydrogen bonding in tetraol molecules facilitates the formation of well-structured and uniform thin films, thereby playing a significant role in advancing EUV lithography.

Presenting Author

Jiyoung Bang received her B.S. degree from Chonnam National University in department of chemistry, and she is currently studying for a Ph.D. in department of chemistry at Chonnam National University. She is focusing on the development of inorganic EUV photoresist

P62

Non-Alkyl Tin Oxo Cluster of CNU-TOC-01(4C-C) as Inorganic Resist for EUV Lithography

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Our study focused on the molecular structure and lithographic properties of a novel resist material, $Sn_4Cl_3(N_2C_3H_4)_2O_4(OH)_4$, named CNU-TOC-01(4C-C), for use in extreme ultraviolet (EUV) lithography. Through field desorption time-of-flight mass spectrometry, we determined the molecular composition of CNU-TOC-01(4C-C) and measured its average particle size using dynamic light scattering. We also quantified the EUV absorption coefficient, crucial for lithographic performance. For lithographic evaluation, CNU-TOC-01(4C-C) was dissolved in ethyl lactate (5 wt%) and spin-coated on SiO_2/Si wafers to produce thin films. These were patterned using either electron beam (E-beam) or EUV radiation, assessing CNU-TOC-01(4C-C)'s adaptability to different lithographic techniques. Post apply bake and post exposure bake were conducted at 180°C and 190°C, respectively, followed by development with a 2.38 wt% TMAH solution. In E-beam lithography, CNU-TOC-01(4C-C) showed a sensitivity of 514.3 $\mu C/cm^2$ and a contrast of 4.8, while, in EUV lithography, it achieved a 22 nm half-pitch resolution at 105 mJ/cm^2 exposure energy. These results highlight the potential of CNU-TOC-01(4C-C) as a promising inorganic resist material for EUV lithography.

Presenting Author

Hyun-Dam Jeong received his B.S. degree in Chemistry from Korea Advanced Institute of Technology in 1990, and continued his studies in the same department, specializing in Physical Chemistry, where he earned his M.S. degree in 1992 and Ph.D. degree in 1996. Following his doctoral graduation, he worked as a Senior Engineer at Samsung Electronics' Semiconductor Research & Development Center, focusing on low-k process development from 1996 to 1999. In 2000, he conducted research on the characterization of porous low-k materials at the Microelectronic Research Center of Georgia Tech in the United States. From 2001 to 2006, he served as the Project Leader and Principal Investigator at Samsung Advanced Institute of Technology, working on ultra low-k material projects and research on solution-processed inorganic semiconductor materials. Since 2006, He has been a faculty member in the Department of Chemistry at Chonnam National University, progressing through the ranks of Assistant Professor, Associate Professor, and Full Professor. His research has primarily focused on the properties of inorganic nanoparticle thin films and quantum dot thin films, and their applications in semiconductors. Recently, he has been investigating the use of inorganic nano clusters and siloxane molecules as metal oxide resists or molecular resists for Extreme Ultraviolet Lithography (EUVL).

P63

The Investigation of the Effect of Electron Beam and Extreme Ultraviolet Irradiation on Dibenzyltin Diacetate Thin Film Using Local Analysis and Quantum Chemical Calculations

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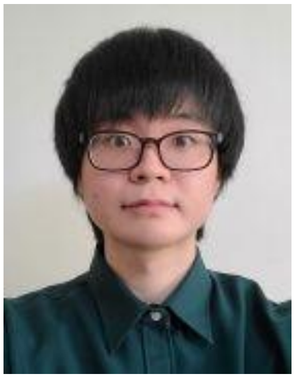
This study investigates the impact of extreme ultraviolet (EUV) light on the chemical alteration of photoresists (PRs), termed EUV-induced material alteration (EUV-MA). EUV-MA plays a pivotal role in photolithography, affecting the manifestation of chemical contrast in PR upon exposure and its subsequent enhancement during development. To estimate the EUV-MA of a PR, one must investigate the changes in the molecular structure of the PR before and after exposure to EUV. However, the limited accessibility of EUV light sources is a constraint in the study. To circumvent this, we utilized electron beam (E-Beam) instead of EUV, based on the similarity in energy distribution of secondary electrons generated by both sources. Our examination focused on the response of dibenzyltin diacetate thin films to E-Beam irradiation, using localized analysis methods such as Fourier-transform infrared spectroscopy (FT-IR) and time-of-flight secondary ion mass spectrometry (TOF-SIMS). Our findings reveal that not only the benzyl group but also the acetate group in dibenzyltin diacetate molecules can dissociate. Additionally, through the natural bond orbital analysis and time-dependent density functional theory calculation of the dialkyltin dicarboxylate series, we established the relationship between their molecular structure and EUV-MA.

Presenting Author

Hyeok Yun received his B.S. degree from the Department of Chemistry at Chonnam National University, and he is currently studying for a Ph.D. in the Department of Chemistry at Chonnam National University. His research focuses on the development of inorganic EUV photoresists.



P64

Synthesis and Characterization of Novel Two-in-One Type Siloxane Molecule Photoresist for EUV Lithography

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In this research, we innovated a photoresist by integrating tert-butoxycarboxyl (t-BOC) and trimethoxysiloxyl (Q) functional groups into a cyclosiloxane structure, aiming to enhance its efficacy in electron beam (E-beam) lithography. The synthesized compound, TS-T4 with t-BOC groups (TS-T4(t-BOC)$_4$), demonstrated exceptional sensitivity, around 1 μC/cm², with 5 kV E-beam exposure. However, at 100 kV, its high sensitivity hindered effective pattern formation. To address this, we explored adding Q groups, synthesizing TS-T4Q$_4$, which showed significantly reduced sensitivity (106 μC/cm²) under 5 kV E-beam. Mixing TS-T4(t-BOC)$_4$ and TS-T4Q$_4$ in a 1:4 molar ratio allowed for the formation of 50 nm half-pitch line/space patterns under 100 kV E-beam, though with some pattern irregularities due to material heterogeneity. Further advancements led to the creation of TS-T4(t-BOC)$_2$Q$_2$ and TS-T4(t-BOC)Q$_3$, balancing both t-BOC and Q groups within a single molecule, resulting in D$_{50}$ values of less than 1 μC/cm² and 3.4 μC/cm² respectively, under 5 kV E-beam. The TS-T4(t-BOC)Q$_3$ impressively demonstrated how Q groups can effectively moderate the sensitivity introduced by t-BOC groups. This research presents significant insights into the design of photoresists for advanced lithography applications.

Presenting Author

Wonchul Kee received his B.S. degree from the Department of Chemistry at Chonnam National University, and he is currently studying for a Ph.D. in the Department of Chemistry at Chonnam National University. His research focuses on the development of inorganic EUV photoresists.

P65

Enabling High-throughput Characterization of Outgassing and Total Electron Yield for Model EUV Resist Materials

Bernhard Lüttgenau, Oleg Kostko, Qi Zhang, Cheng Wang, Meng Zhang,
Ricardo Ruiz, and Michael Connolly

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Understanding the behavior of generated electrons in polymer thin films under extreme ultraviolet (EUV) and soft X-ray radiation is crucial for developing high-performance EUV photoresists for nanopatterning. Especially for future technology nodes, where electron blur from traveling electrons could contribute to defect formation. To explore the impact of different resist materials on the generation and time-dependent behavior of slow electrons (below 20 eV) and their role in molecular bond scission, we need to analyze a wide range of samples (102 - 103) using various techniques like residual gas analysis (RGA) or total electron yield (TEY) analysis. We present a setup infrastructure enabling simultaneous outgassing and TEY measurement for various model EUV resist materials within minutes per sample. This setup facilitates high-throughput characterization of slow electrons and EUV induced chemistry on EUV photoresist, deepening our understanding of EUV resist processes. Initial combined measurement results are presented and discussed, alongside proposed improvements to enhance throughput and allow for additional in-situ characterization techniques in the future.

Presenting Author

Dr. Bernhard Lüttgenau is a postdoctoral scholar at Lawrence Berkeley National Lab. He received his doctoral degree in 2024 from RWTH Aachen University, Germany, where he conducted research on EUV interference lithography employing partially coherent EUV sources. His current research focuses on the fundamental characterization of EUV resist materials using advanced spectroscopic techniques with EUV and soft X-ray radiation.

P66

Investigating Influence of Electron Affinity on Electron Emission in EUV Photoresists

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Understanding the fundamental properties of photoresists in extreme ultraviolet (EUV) photolithography, including the behavior of electrons emitted electrons from the during exposure for of photoresists, is crucial in semiconductor manufacturing, particularly as lithographic demands increase with the shrinkage of semiconductor device sizes. In this context, this study investigates the effect of materials with varied electron affinities on the ratio yield of slow and fast electrons emitted by exposed photoresists, shedding light on material effects and lithographic performance. In this experimentwork, we added various chemical substances (Trityl, triphenylamine, anthracene, etc.) , which have similar molecular weight or chemical structure but different electron affinities, to model photoresists. We then conducted PES (Pphotoelectron Sspectroscopy) on each resist sample and compared the intensity ratio of slow electrons (with energy below 20 eV) and fast electrons emitted by exposed photoresists. By doing so, we analyzed how the electron affinitiesy of chemical substances could influence the electrons generated by EUV lithography. Based on this study, our research aims to bridge theory and practice, catalyzing advancements in semiconductor fabrication.

Presenting Author

Honggu Im, Ph.D., earned his doctorate in chemistry from KAIST, specializing in organic synthesis and synthetic methodology. He then directly joined Samsung Electronics' Semiconductor Research Institute as a senior engineer, specializing in photolithography processes and material development related to EUV photolithography. Currently, Im is a postdoctoral scholar at Lawrence Berkeley National Laboratory, where he conducts fundamental research on EUV resist characterization and mechanisms. His discoveries include correlations between materials and lithographic performance, demonstrating his continued dedication to advancing the field of material science and research for semiconductor.

P67

EUV CAR-NTD with New Developer for Chemical Stochastic Defect Reduction

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In 2019, finally, extreme ultraviolet (EUV) lithography has been applied to high volume manufacturing (HVM). However, the performance of EUV resist materials are still not enough for the expected HVM requirements, even by using the latest qualifying EUV resist materials. The critical issues were the stochastic, which will be become defectivity. The analyzing summary of the stochastic factors in EUV lithography was reported, which described 2 (two) major stochastic issues, which are photon stochastic and chemical stochastic [1]. The chemical stochastic means caused from resist materials and processes for lithography, materials uniformity in the film, reactive uniformity in the film, and dissolving behavior with the developer. For chemical stochastic reduction, newly proposed novel formulated organic solvent-based developer for negative-tone development of chemically amplified resist (CAR) with EUV exposure, called EUV CAR-NTD were applied. The lithographic performance of new functional materials introduced EUV CAR-NTD will be discussed. The possibility of EUV CAR-NTD will be proposed.

[1] T. Fujimori, *J. Photopolym. Sci. Technol.*, **35**, 35 (2022).

Presenting Author

Nishiki Fujimaki, is a Researcher of FUJIFILM Corporation.
He received B.S. and M.S. degrees in applied chemistry from Osaka University, Japan, in 2012 and 2014, respectively. In 2014, he joined FUJIFILM Corporation as a researcher in Electronic Materials Research Laboratories, where he has been engaged in photo resist materials and process technology. From 2017 to 2020, he had been working at imec as an assignee from FUJIFILM.

P68

Dry Development Process for Vertically Tailored Hybrid Multilayer EUV Photoresist

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Kwangsub Yoon, Myung Mo Sung and Jinho Ahn

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CH^{3}IPS (Center for Hyperscale, Hyperfunction, Heterogeneous Integration
Pioneering Semiconductor Technology)

Extreme Ultraviolet Lithography (EUVL) has been implemented in high-volume manufacturing (HVM) for the production of advanced semiconductor devices, including the 5 nm technology node and beyond. However, the persistent challenge of resist pattern collapse hinders the process window for effective resist patterning. To address this issue, the dry development process has been introduced to mitigate pattern collapse. This dry development process allows for a larger collapse-free process window, eliminating the capillary forces inherent in wet development processing.

This study explores the dry development characteristics of vertically tailored hybrid multilayer EUV photoresist [1]. We compare the dry development characteristics by applying halide-based gas in both plasma and vapor types to the vertically tailored hybrid multilayer EUV photoresist. Through a comparison of dry development performance based on process type, we propose an appropriate dry development process for the vertically tailored hybrid multilayer EUV photoresist.

[1] M. Sung, “Vertically tailored hybrid multilayer EUV photoresist with vertical molecular wire structure”, SPIE proc. 12953, 12953-48 (2024)

Presenting Author

Ji-Hoo Seok received her B.S. degrees from Kongju University and M.S. degree from Sungkyunkwan University. She worked as a process engineer at SEMES, a semiconductor equipment company in the Republic of Korea. Currently, she is a Ph.D. student in Materials Science and Engineering at Hanyang University, working under the supervision of Professor Jinho Ahn. Her research topic focuses on a dry development process for EUV photoresist.

P69

Evaluation of C-beam Generated EUV Lightning Source using Mirror and Filter Technique

Umesh Balaso Apugade[1], Kyu Chang Park[1]

[1]Department of Information Display, Kyung Hee University, Seoul, The Republic of Korea

Extreme ultraviolet light (13.5 nm wavelength) source is a core technology for next-generation semiconductor processing. At present, leading-edge research is underway in multiple countries focused on nanopatterning next-generation semiconductors at the nano meter scale or beyond, and the significance and utilization of extreme ultraviolet (EUV) exposure equipment are experiencing a growing trend in this production process.

We are aiming to develop a simple and powerful portable EUV lightning source, this source could be applied for EUV transmittance and reflection measurement with three different isolated compartments Fig 2, (Light zone, beam enhancement zone and measurement zone) in order to reduce debris, reduce visible light effect, out-of-band radiation in the ultraviolet, and infrared. Further, we will show the application of generated EUV to the patterning of polymethyl methacrylate (PMMA) photoresist utilizing specific filters. Furthermore, this method offers promising advancements as an inspection tool for mask, pellicles and materials.

We utilize traditional photolithography with positive photoresist to create a dot pattern array on a silicon wafer. Further by using triode direct current plasma-enhanced chemical vapor deposition (PECVD) technique vertically aligned Carbon Nano Tube (CNT) were grown on the patterned Si wafer. As grown CNT has a dot diameter 2.5-3.5 μm and height 40 - 45 μm Fig. 1. Next, we developed a simple and novel cost effective EUV light source using a CNT-based cold cathode electron beam triode system to irradiate Tin (Sn) and generate EUV light. This method then verified using with EUV reflective optics, specific filters and a photodiode (SXUV100, OPTODIODE at 13.5 nm wavelength). After implementing filter and mirror technique, we achieved EUV efficiency about I_{ph} measurement at M2 position is ~6.00 $\times 10^{-10}$ mA which is significantly differs from M1 position 1.02 $\times 10^{-10}$ mA i.e., 58 % reduction of visible light effect measured at designated zone as in fig 2.

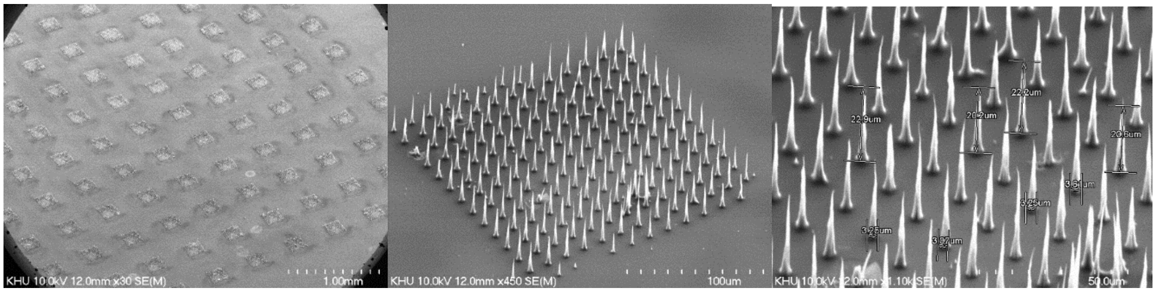
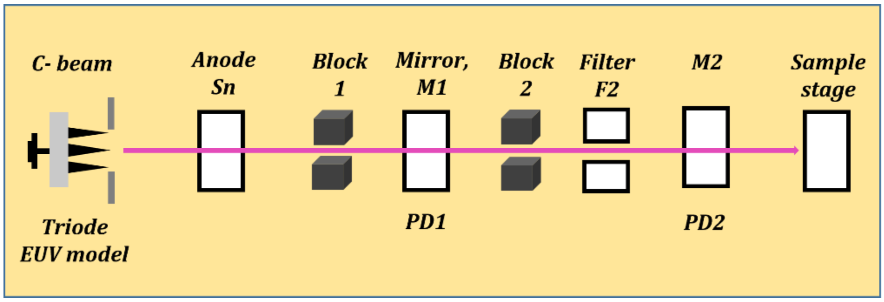


Figure.1 SEM images of Vertically aligned Carbon Nano Tube (CNT), with dot diameter 2.5-3.5 μm, height 40 - 45 μm.



Position Terminology	
Dark	D (Blocked)
M1	Mirror' Photodiode 1
M2	Photodiode 2
Filter F1	Between Anode & M1
Filter F2	Between M1 & M2

Figure.2 Schematic layout of EUV beamline until end station at the photodiode. (Black body shows the blocking)

Presenting Author

Mr. Umesh Balaso Apugade, is a an Integrated PhD Student in the Department of Information Display in the Kyung Hee University, Seoul 02447, South Korea.

P81

Synchrotron-based EUV metrology at PTB (Invited)

Richard Ciesielski

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PTB is Germany's national metrology institute, supporting partners from industry and science in Europe and worldwide with measurements and know-how through joint research projects. At the synchrotron radiation facilities "Metrology Light Source" (MLS) and "BESSY II" in Berlin, PTB uses radiation in the THz, IR, UV, EUV, VUV, and soft X-ray spectral ranges for basic and applied metrological tasks. For more than 25 years, the EUV-Radiometry group develops and provides metrology services for the characterization of optical components and radiation detectors as well as the measurement of optical material. PTB offers services to determine the spectral responsivity of radiation detectors in the full spectral range from UV to X-ray, using the synchrotron as a radiation standard. The EUV radiometry group uses several measurement stations at the storage rings BESSY II and MLS: an EUV reflectometer which can accommodate large optical components like collector mirrors for EUV plasma sources, an EUV Ellipso-Scatterometer for reticle-size samples supporting measurements of reflection and scattering under arbitrary polarization conditions, and a compact end station for hybrid investigations of nanostructured samples. Most recently PTB also hosts an online catalogue of optical material constants for pure and compound materials in the EUV spectral range [1].

[1] https://ocdb.ptb.de

Presenting Author

Richard Ciesielski received his Ph.D. from LMU Munich on time-resolved microscopy in 2016, where he later was working on hybrid perovskite's material properties. Since 2020 he works at PTB focusing on EUV Nanometrology using synchrotron radiation. His research activities include the determination of optical constants through soft X-ray reflectometry, the reconstruction of nanoscale grating structures from EUV scatterometry, and beamline design for future applications.

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Applications of EUV Metrology Tools

Matt Hettermann

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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.

Presenting Author

Matt Hettermann is the VP of R&D at EUV Tech, a leading provider of at-wavelength EUV metrology tools.

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Preparing the Availability of EUV Light Sources for High Volume Manufacturing

Henry Chou

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Extreme Ultraviolet (EUV) lithography is gaining adoption in the next generation of high-density chip manufacturing. To support high volume manufacturing, reliable inspection equipment must be available commercially. EUV light sources are the powertrain to these inspection tools and requires a high level of performance, stability, and low cost of ownership. Energetiq Technology has been offering high performing EUV light sources for nearly 20 years and is on the forefront of reliable light sources integrated into commercially available equipment. Top applications are actinic mask/blank inspection, wafer/resist exposure, and optical component inspection systems. These systems must accurately and reliably inspect critical components before they are used in the lithography process and can mitigate the risk of defects that result in yield loss on the printed wafers. Energetiq will discuss their technology, products and roadmap to support EUV lithography for HVM.

Presenting Author

Henry Chou is the Director of EUV Marketing at Energetiq Technology responsible for sales, service, and product management. Henry received his BS in electrical engineering at the University of Notre Dame and EMBA at Baruch College, CUNY. Henry has worked for various capital equipment suppliers in the semiconductor, renewable energies, and consumer electronics industries.

P84

Nanoscale Chemical Analysis of EUV Resists

Derek Nowak, Tom Albrecht, Sung Park

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With the growing adoption of EUV lithography, the need for new metrology methods with greater sensitivity and higher spatial resolution to analyze the photolithographic process is becoming acute in order to shed light on the stochastic effects that govern the line edge roughness of the patterned lines. Since the stochastic effects arise from chemical changes due to the discrete absorption of photons by photo or electron-active chemical components that are distributed non-uniformly in nanoscale, a tool that can monitor subtle chemical changes with nanoscale spatial resolution would be ideal in understanding the relationship between photo-chemistry and the final resist structure. In this paper, a relatively new nanoscale technique called infrared photo-induced force microscopy (IR PiFM), which combines atomic force microscopy (AFM) and infrared (IR) spectroscopy with sub-5 nm spatial resolution, is introduced. By utilizing a state-of-the-art tunable broadband IR laser (tunable from ~550 to > 4000 cm-1 with ~ 3 cm-1 spectral width over the entire range), truly nanoscale PiF-IR spectra that agree with bulk FTIR spectra can be acquired. Due to excellent repeatability, PiF-IR spectra can be used to monitor subtle chemical changes even on ultrathin films. The talk will share some preliminary results on the analysis of latent images on a chemically amplified resist and a metal oxide resist.

Presenting Author

Thomas R. Albrecht is VP of Engineering and Technology at
Molecular Vista, Inc.

P85

TNO EUV Materials Research for EUV Infrastructure (Invited)

J. van Veldhoven, H.H.P.Th. Bekman

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In this presentation we will give an overview of the services that TNO can provide to the EUV community. With its EUV beam line, but also with a large variety of other test setups, TNO can evaluate the performance of materials in an EUV environment. Examples will be given for reticle absorber qualification and pellicle development studies. TNO is an independent research institute partly funded by Dutch and European governments to support the industry with innovation and new technologies. The majority of the projects for industrial applications are based on contract research and are company confidential. TNO has been and still is in close cooperation with ASML and Carl Zeiss since the beginning of the EUV development in 2000. Much of the knowledge developed by TNO is now being used for screening of materials and modules for EUV applications.

Presenting Author

Jacqueline van Veldhoven holds a Ph.D. in physics from the University of Nijmegen. She did here PhD partially on the Max-Planck-Institut in Berlin where she studied the spectra of cold molecules. After graduation she joined TNO and first worked on sea mine detection. Later she joined the department within TNO working on EUV optics lifetime for ASML and Carl Zeiss. She has been active in various fields from EUV plasma sensor development to studying the interaction of EUV (-plasma) with materials. For the latter she became an XPS expert.

P86

Veeco Ion Beam Deposition Advancement and Diamond Like Carbon as Novel Material for EUV Mask Blanks (Invited)

Meng Lee

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As the semiconductor industry progresses towards advanced technology nodes for future logic and memory devices, the adoption of extreme ultra-violet (EUV) lithography becomes increasingly prevalent. This acceleration involves the integration of more EUV layers per device and the imminent adoption of high numerical aperture (NA) techniques to propel the industry forward. Consequently, there is a critical need to enhance the optical and particle performance of EUV mask blanks to meet the escalating demands of advanced technology nodes. EUV mask blanks necessitate meticulous particle control during the deposition of complex Molybdenum (Mo) and Silicon (Si) multilayer film structures, complemented by a Ruthenium (Ru) capping layer.

At Veeco, our focus lies in refining the deposition process of EUV mask blanks' Mo/Si multilayers and Ru capping layers through Ion Beam Deposition methods. This endeavor aims to optimize particle defect reduction, reflectivity enhancement, film uniformity, and overall mask blanks yield. Our efforts extend to exploring hardware enhancements aimed at reducing nodules on the target material to mitigate overall particle contamination. Additionally, we are scaling the ion source design to enable greater process flexibility. Furthermore, we are investigating the potential of novel materials such as Diamond-like Carbon (DLC) to replace the Ru capping layer and minimize reflectivity degradation.

This presentation offers an overview and progress update on Veeco's Ion Beam Deposition technology roadmap, along with a summary of developments in Diamond-like Carbon (DLC) research initiatives.

Presenting Author

Meng Lee is the Senior Director of Product Line Marketing at Veeco Instruments Inc. Currently, he oversees the Ion Beam Deposition and Etch, Diamond Like Carbon, Physical Vapor Deposition, Lapping, and Dicing product lines at Veeco's Plainview location. With over 28 years of experience in the capital equipment business, Meng has been instrumental in driving significant technological advancements and roadmaps to cater to diverse markets, including next-generation ion beam deposition and ion beam etch technology for EUV mask. He is a co-author of over 20 technical papers on EUV mask blanks with his EUV team. Meng holds a Bachelor of Science degree in Electrical and Electronics Engineering from Louisiana State University, earned in 1994, and a Master of Administration (MBA) from California Lutheran University, obtained in 2005.

P87

Interlayer 3D-EPE Analysis using Contour Distance from Design with High Landing Energy SEM Imaging on Advanced Logic Devices (Invited)

Michael Shifrin

AMAT

Presenting Author

P102

Nanoscale Photon Sensing

Maurice Garcia-Sciveres

Lawrence Berkeley National Lab

The pixel size of imaging devices is normally constrained by the diffraction limit of the light being detected. However, this is a classical wave constraint. Treating photons as particles and considering the interaction of the photon field with the detector as a single quantum system leads to novel approaches for optimal detection performance, including 100% quantum efficiency together with single photon spectral information, by using nanoscale detection elements much smaller than the wavelength of light. Realizing this novel type of sensor appears possible with emerging methods of heterogeneous integration of nanomaterials on CMOS. The path towards a demonstrator device will be described.

[1] Citations (if applicable)

Presenting Author

Maurice Garcia-Sciveres received his PhD from Cornell in 1994 for the measurement of the weak mixing angle Vcb in the CLEO e+e- collider experiment. He was a postdoc, then scientist, and now senior scientist at Lawrence Berkeley National Lab, where he worked on Fermilab's CDF and CERN's ATLAS experiments. He focused on development of readout integrated circuits for silicon vertex detectors, and was recognized for his contributions in this area with an APS fellowship in 2015. In 2013 he co-founded the CERN RD53 collaboration to develop pixel detector readout chips for the ATLAS and CMS experiments, and has served as co-spokesperson since. Since 2018 he has been PI for the LBNL Quantum Information Science Enabled Discovery (QuantISED) program, and since 2021 PI for the "Co-Design and Integration of Nano-Sensors on CMOS" project at LBNL.

P103

Characterization of Chemical/structural Information of Latent Image via Critical-dimension Resonant Soft X-ray Scattering

Cheng Wang

Advanced Light Source, LBNL

The adoption of EUV lithography has facilitated the reduction of device dimensions; however, the corresponding scaling of variability, such as line edge and width roughness (LER/LWR), has remained a challenge. These inherently stochastic parameters negatively affect device reliability and energy efficiency. Identifying the origins of these effects is challenging, as they cannot be detected until after the final dissolution step. In this study, we present our recent findings using critical-dimension resonant soft X-ray scattering (CD-RSoXS) to examine the scattering behavior of photoresist materials. Our primary goal is to understand the contributions of each process step to the generation of LER/LWR, as well as footing/scumming. A crucial part of this investigation involves our ability to measure the presence of these features following the exposure step, during which a latent (chemical) image is stored within the photoresist. RSoXS leverages tunable soft X-ray sources to significantly enhance the scattering cross-sections from heterogeneous materials. This enhancement offers valuable insights into sub-nanometer spatial resolution and local chemical sensitivity simultaneously. To obtain a comprehensive profile of the latent image, we use distorted wave Born approximation (DWBA) and Finite Element Method (FEM) for the reconstruction of line shapes and LER/LWR.

Presenting Author

Dr. Cheng Wang is a Physicist Staff Scientist at the Advanced Light Source, Lawrence Berkeley National Lab. He obtained his bachelor degree in physics from Jilin University, China in 2002, and received his Ph.D. in physics in North Caroline State University in 2008. After graduation, he joined the ALS, LBNL where he led the development of Resonant Soft X-ray Scattering for soft materials and the construction of a dedicated facility at ALS Beamline 11.0.1.2. His research interest is to develop and utilize advanced synchrotron x-ray probes such as soft x-ray scattering, spectroscopy to elucidate the morphology, chemistry and interfacial structure of broad range of complex materials.

P105

Spatially Resolved EUV Resist Dissolution

Paul Ashby

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Continued lithographic scaling using high-NA EUV scanners requires materials and processes with sufficient resolution and stochastic performance to translate the aerial image into thin film photoresist material. Amongst these key processes is photoresist dissolution that converts latent exposure chemistry in the photoresist into a developed pattern. However, co-optimization of resist materials and the develop process is difficult due to the challenge of directly measuring resist dissolution at the nanometer spatial and sub-second temporal scales on which it occurs. We developed an in-situ dissolution rate monitoring technique using high-speed atomic force microscopy (AFM) based on spiral scanning that uses a specially-designed flow cell which provides precise control of the time at which developer is introduced to the photoresist material, as well as delivery of nearly full-strength developer in fractions of a second. At 10 frames per second and 5 nm resolution , our system offers the ability to probe the spatially-dependent nature of the dissolution process at conditions close to those in the fab, providing insight into exposure-dependent dissolution rate gradient, material swelling, and other potentially lithographically relevant phenomena such as polymer entanglement.

[1] Long, L.; Chen, J.; Neureuther, A.; Naulleau, P.; Ashby, P., *Spatially resolved dissolution monitoring using AFM*. SPIE: 2022; Vol. 12292, https://doi.org/10.1117/12.2643273.

Presenting Author

Paul Ashby is a staff scientist in the Imaging and Manipulation Facility of the Molecular Foundry at LBNL. His lab seeks to develop functional soft materials through the purposeful design of information dense molecules and understanding the factors that drive their assembly and organization. Further, it advances soft matter characterization through the development of in-situ scanned probe microscopy tools.

P106

A Holistic Approach to Patterning Science at Berkeley Lab

Ricardo Ruiz

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The Center for High-Precision Patterning Science (CHiPPS), a DOE-funded Energy Frontiers Research Center, addresses challenges in semiconductor patterning with EUV photon energy. We focus on efficiently utilizing high-energy photons for nanoscale patterning and mitigating stochastic effects that limit precision. Our holistic approach integrates fundamental studies of light-matter interactions with co-designed materials and processes. Our research includes sequence-defined and nanostructured hybrid photoresists, molecular-level solvation control, and self-assembling materials to minimize stochastic variability. Leveraging a state-of-the-art EUV patterning, Nanofabrication and X-ray characterization facilities at Berkeley Lab, we aim to achieve atomic/molecular precision in pattern transfer. Our presentation highlights CHiPPS' efforts in high-precision patterning, with a focus on the unique capabilities co-located at Berkely Lab.

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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