2025 EUVL and Source Workshop

Workshop Abstracts

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IBM Lithography Roadmap and Need for Future Lithography Tools (Keynote)

Allen Gabor

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Semiconductor lithography resolution has been driven by decreasing wavelength and increasing NA for the last fifty years. Future technology scaling requirements necessitate continued improvements in lithographic tooling beyond "high" 0.55 NA EUV exposure tools. This presentation will review outlooks for technology pitch scaling, timing and potential options for future lithographic tooling. Both "hyper" 0.75 NA EUV and shorter wavelength at low NA potential tools will be examined. The implications of future wavelength and NA choices on depth-of-focus, stochastic induced edge placement error and design-rule flexibility will be described. Robust three-beam imaging, at pitches the semiconductor industry will need to be patterning in the 2nd half of the next decade, can be achieved if lithography tools utilizing wavelengths shorter than 5nm and NAs less than 0.4 can be built.

Presenting Author

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

P2

Update on High-NA EUV in process technology development (Keynote)

Steven Carson

Intel

High-NA EUV (0.55NA) scanners are now available to developing processes, enabling tighter pitch design rules with simplified integration schemes. Just as 0.33NA EUV adoption simplified integrated process strategies with respect to multi-patterning 193i technologies, 0.55NA EUV brings the opportunity for decreased mask layer counts and simplified integrated process. The early High-NA scanner systems are demonstrating acceptable introductory levels of performance, and if they can mature quickly, IDM's have the opportunity to avoid the burdens of increasingly complicated multi-patterning schemes associated with 0.33NA EUV.

The scope of technology changes in moving from 0.33NA to 0.55NA EUV are significantly reduced with respect to the revolution from optical to EUV lithography. The anamorphic optical design constrains the High-NA EUV field size to half of the optical and 0.33NA EUV limit. Throughput implications of the High-NA half-field design have been offset with faster stages and higher power sources, while the systems maintain and improve overlay, imaging, and defectivity performance to enable the lithography patterning roadmap.

This presentation will review the status of the High-NA EUV lithographic equipment, the state of the High-NA ecosystem, and the current capability of 0.55NA EUV in process technology development and towards high volume manufacturing.

P4

Research & roadmap for future sources of EUV light and beyond (BEUV) (Keynote)

Oscar Versolato

Advanced Research Center for Nanolithography (ARCNL), Science Park 106, Amsterdam

The successful insertion of EUV lithography in high-volume manufacturing was enabled through several decades of collaborative work between industry and academia. The short, 13.5-nm EUV wavelength enables patterning the smallest, smartest, and most efficient features on chips. Historically, in the push for optical resolution of the patterning, every major reduction in wavelength is followed by improvements in the imaging numerical aperture until limitations therein lead to the introduction of a shorter wavelength to enable even finer patterns. Increasing NA (High-NA, Hyper-NA, …) calls for ever more powerful sources of EUV light where, as this talk will detail, 2um laser produced plasmas show particular promise. It is also time to consider lithography, and metrology for lithography, using wavelengths shorter than 13.5nm, beyond EUV (BEUV). Such wavelengths may, e.g., be generated from laser-produced plasma (LPP) using heavier elements, but fundamental understanding of the atomic and plasma physics is very much incomplete. This talk will review ongoing activities on 13.5nm LPPs as well as sketch a research roadmap for BEUV light source developments based on input of the Blue-X Consortium's Technical Working Group on Source.

Presenting Author

Oscar Versolato received his PhD in 2011 from the University of Groningen, The Netherlands, for work on laser spectroscopy on trapped, short-lived radium ions. He did postdoctoral work at the Max-Planck-Institute für Kernphysik in Heidelberg, Germany, on spectroscopy and sympathetic laser cooling of highly charged ions (with PTB Braunschweig, DE), and molecular ions (with Aarhus University, DK). He has been working on Source research at ARCNL starting 2014 and since 2019 he is a tenured group leader of the EUV Plasma Processes group at the Advanced Research Center for Nanolithography (ARCNL) appointed at Vrije Universiteit Amsterdam, where he was promoted to Full Professor in 2025. His present research interests include plasma sources of extreme ultraviolet radiation, droplet deformation and fragmentation after laser pulse impact, physics of highly charged ions, and spectroscopy. He was awarded the 2016 NOW Vidi research grant, as well as the 2018 ERC Starting and 2022 ERC Consolidator grant. He is the head of the Source Department at ARCNL, and is part of the management team at ARCNL and, separately, also at Vrije Universiteit.

P5

We Can Make a Difference – How to Promote Women in Technology (Keynote)

Debbie Gustafson

Energetiq

In today's rapidly evolving technological landscape, personal stories of success serve as powerful inspirations. This keynote speech will share my journey of becoming a successful CEO of an EUV Source Company, highlighting the challenges I faced and the strategies I employed to overcome them. We will explore the importance of diversity and inclusion, examining how these helped Energetiq become the leading supplier of EUV Sources for Mask Inspection. By sharing my experiences and practical strategies, this speech aims to empower and motivate individuals to champion gender equality in technology. Together, we can create a more inclusive and dynamic future, where women are not only participants but leaders in shaping the technological advancements that define our world.

Presenting Author

Debbie is the CEO of Energetiq Technology, a manufacturer of high brightness EUV light sources. Debbie's strategic vision, operations skillset and commitment to building strong customer relationships has led the company to rapid global growth. Debbie works tirelessly to change the face of the technology industry and is committed to building diverse teams, especially opening doors for other women in tech and mentoring them through their experiences. She has served on the SPIE Board of Directors and is also a member of the SEMI Foundation Board.

P6

Development of Next-Generation Semiconductor Process Technologies for EUV and BEUV under Japan's "K Program" for Economic Security by JST (Keynote)

Junji Yumoto

The University of Tokyo
Japan Science and Technology Agency (JST)

As part of Japan's efforts to enhance the synergy between national security and stable economic activity, a new funding initiative, the "K program" was launched in 2022. (K program; Key and Advanced Technology R&D through Cross-Sectional Collaboration Program) This program targets various fields, including next-generation semiconductors, quantum technology, AI, and biotechnology, and promotes research and development of advanced fundamental technologies and practical application of the results, not only for consumer but also for public use.
To date, JST has launched about 20 research and development initiatives under this program. Among them, the project on "Next-Generation Semiconductor Process Technology" was initiated on April 1 of this year.
This project aims to establish innovative foundational technologies that are essential for the future advancement of EUV and BEUV semiconductor process technologies. The following six R&D areas are being pursued:

- Foundational technology for solid-state drive lasers aimed at energy-saving EUV exposure systems
- Foundational technology for free-electron lasers to realize next-generation EUV light sources
- Processing and coating technologies for large-diameter, high-precision mirrors
- Multilayer reflective coating technologies required for BEUV optical systems
- Development of high-sensitivity and high-resolution resists
- Development of nonlinear optical materials for coherent light generation at wavelengths around 170 nm and their applications

In this presentation, we will introduce the specific research activities in these areas.

Presenting Author

Junji Yumoto received his Doctor of Engineering degree from Keio University in 1984 and began his career at Nippon Telegraph and Telephone Co. (NTT). He held several leadership roles at NTT, including Director of NTT Basic Research Laboratories and Director of NTT Photonics Laboratories, and later served as President of NEL America, Inc. based in New Jersey (now NTT Devices America, Inc.). In 2014, he was appointed Professor at the University of Tokyo, where he also served as Director of the Institute for Photon Science and Technology. Since 2021, he has been Professor Emeritus and Project Professor at the University of Tokyo, and currently serves as Program Director of the JST Program for the Development of Next-Generation Semiconductor Process Technologies.

P7

EUV and Non-EUV Based Lithography R&D to Extend Semiconductor Device Scaling and Improve Manufacturing Efficiency (Keynote)

Robert Chau

Natcast Senior VP of Research

With 0.33 NA EUV being used in high volume manufacturing and 0.5 NA EUV making good progress towards production, semiconductor communities globally are initiating and driving R&D efforts on evolutionary and revolutionary technologies in improving lithography performance and extending the EUV roadmap beyond 0.5 NA EUV. Exciting research on coherent light sources [Ref. 1], EUV resists, shorter (<13.5nm) wavelengths, directed self assembly (DSA) lithography, etc, is currently being carried out world-wide. In addition, non-EUV based lithography such as nanoimprint lithography has recently made good progress and is considered a more economical alternative to EUV for producing circuit features down to 14nm [Ref. 2]. In this presentation I will describe how NSTC and Natcast can help facilitate and drive both EUV and non-EUV based lithography R&D and create innovations in improving U.S. semiconductor manufacturing efficiency and technology performance.

[1] "On the compatibility of free-electron lasers with EUV scanners." Accessed: Mar. 21, 2025. [Online]. Available:https://www.spiedigitallibrary.org/conference-proceedings-of-spie/12953/3012412/On-the-compatibility-of-free-electron-lasers-with-EUV-scanners/10.1117/12.3012412.short
[2] "Canon Delivers Nanoimprint Lithography to Compete with EUV - IEEE Spectrum." Accessed: Mar. 21, 2025. [Online]. Available: https://spectrum.ieee.org/nanoimprint-lithography

Presenting Author

Dr. Robert Chau joined Natcast in 2024 after spending 36 years in semiconductor R&D at Intel Corporation, where he was promoted to Intel Fellow in 2000 and to Intel Senior Fellow in 2005. From 2014 – 2022, Dr. Chau was the General Manager of Intel Components Research group responsible for driving Intel's internal semiconductor and packaging research and external R&D engagements. In 2022, Dr. Chau became the Director of Intel Europe Research and relocated from the U.S. to Europe, where he was responsible for establishing Intel's semiconductor R&D infrastructure across Europe and expanding its partnership with the European R&D ecosystem to develop enabling innovations for Moore's Law extension and future advanced microelectronics. Dr. Chau received numerous semiconductor industry awards, holds more than 490 U.S. patents, and is an IEEE Fellow and an elected member of the U.S. National Academy of Engineering.

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EUV multilayer optimization for next-generation EUVL - 13.5nm/11.3nm high-NA and 6.6nm/WW opportunities (Keynote)

Bruce W. Smith

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82 Lomb Memorial Dr., Rochester, NY 14623

As EUVL is now being used for high volume manufacturing at 0.55NA, the likelihood of higher NA values is increasing. These advances are driving careful consideration of materials and system design, along with lithographic effects such as multilayer reflected phase, polarization losses, and correlated aberrations. A depth-grading approach to optimizing multilayers is presented, utilizing the EUV optical properties of constituent materials to achieve improved angular and spectral performance. By considering high-order, polarization-dependent phase effects, errors that contribute to multilayer-induced aberration can be minimized, extending high-angle reflection for mask and optical coating application. Solutions for Mo/Si multilayers at 13.5nm and Ru/Be multilayers at 11.3 nm are introduced, together with La/B multilayers at 6.6 nm and multilayer candidates for the 2.2-4.4nm water window. Trade-offs will be presented, including scatter effects at short wavelength, spectral bandwidth, angular bandwidth, and polarization effects.

Presenting Author

Professor Bruce Smith is a Distinguished Professor of Electrical and Microelectronic Engineering at the Rochester Institute of Technology (RIT). Professor Smith and his group carry out research in areas of micro- and nano-fabrication including nanolithography, semiconductor processing, thin film materials, and optical engineering. Their work is directed toward leading edge electronic, photonic, micromechanical, and display devices and structures involving both DUV and EUV nanotechnology. Professor Smith has received numerous awards from academic and professional organizations, and is a Fellow of the IEEE, Optika (OSA), and SPIE. Professor Smith has published over 200 papers, presented over 50 keynote, plenary, or invited talks, and authored several book chapters. He holds over 30 patents in technology including nanolithography illumination systems, semiconductor masking devices, optical system design, and semiconductor materials engineering.

P11

EUV Absorber Sidewall Metrology with EUV Scatterometry (Invited)

Stuart Sherwin, Matt Hettermann, Dave Houser, Luke Long, Patrick Naulleau

EUV Tech (United States)

Feature sizes on EUV photomasks are rapidly shrinking to accommodate higher resolution patterns and sub-resolution features. However, as feature size decreases on the mask, EUV scattering becomes increasingly sensitive to Mask 3D effects, which depend on the 3D absorber profile. Therefore, there is an increasing need to accurately measure and control the 3D profile of etched absorber structures on EUV photomasks. Furthermore, EUV radiation is an ideal probe for measuring an EUV photomask, due to its short wavelength, high reflectivity near normal incidence, and sensitivity to all EUV optical effects. We present a method for measuring the CDU and the sidewall angle (SWA) of EUV photomasks using EUV scatterometry, along with an experimental demonstration of the method on the EUV Tech ENK tool.

P12

Reduction of Wafer Intra-Field Overlay and CDU Residuals via laser processing of EUV Reticles (Invited)

Yogev Baruch[1], Avi Cohen[1], Hillel Zalcman[1], Daniella Vidal[1], Sami Amer[1]

[1]Carl Zeiss SMS Ltd, HaDolev 3, 2015600 Bar Lev Industrial Park, D.N. Misgav, Israel

The EUV lithography process is entering a HVM (high volume manufacturing) phase for the past several years and already constitutes a key and indispensable step in the high-end IC (integrated circuits) manufacturing workflow. Despite significant performance breakthroughs, and enduring efforts for process and manufacturing solutions to robustness and performance requirement fulfilment, some undesired process residuals still exist after the lithography step. A critical among them is the EPE (edge placement error) which has a negative effect on the HVM robustness and the overall chip performance. Research and data analysis already revealed that contributors to the EPE are the wafer intra-field overlay residuals and the CD (critical dimension) uniformity residuals. Both being errors that can be reduced by the ZEISS tuning technology

The ZEISS ForTune EUV system, utilizes a high-power, ultra-short pulse laser and a precise optical setup to generate a unique expansion element which are inscribed into the reticle substrate. These expansion elements have the ability to modify the reticle substrate to finally affect the mask image placement errors in a well-defined and accurate solution. This allows to significantly reduce the wafer intra-field overlay residuals during the EUV lithography process with high lateral control resolution, thus reducing the overall EPE.

The ZEISS ForTune MLM (multilayer modification), which is now in an advanced development stage and nearing market product release, utilizes a state-of-the-art ultra-short pulse laser and optical setup which allows intra-volume modification of the EUV mask multilayer stack reflectance in a very localized way. This modification affects the dose at wafer to finally control the intra-field CD uniformity during the EUV lithography process at a very high lateral control resolution. The process contributes to the reduction of the overall EPE.

Scope of this contribution is to review both technology concepts and to present use cases including first results addressing intra field overlay and CD residuals.

KEYWORDS: EUV lithography, CD uniformity, EPE, ForTune EUV, Intra field overlay, laser, ForTune MLM, high lateral resolution, EUV mask

Presenting Author

Yogev Baruch is an experienced application engineer at ZEISS SMS Ltd., focusing on the implementation of the advanced masks Tuning products at the high-end IC manufacturing industry. Yogev received his BSc in mechanical engineering at the Ort Braude College.

P13

Hyper-NA EUV Imaging, and Beyond (Invited)

Markus Benk

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The first High-NA EUV scanners have been installed in the field. The reported performance of these systems suggests that High-NA EUV lithography could enter production very soon. The ASML technology roadmap shows Hyper-NA EUV lithography at 0.75 NA as the proposed extension to EUV lithography with an insertion date after 2030. Lithography at wavelengths below 13.5 nm is also under consideration to extend patterning towards future nodes.

SHARP is a synchrotron-based actinic EUV mask microscope, dedicated to research in photomask technology and EUV imaging. The SHARP microscope has been supporting the introduction of 0.33NA EUV lithography since 2013. We added anamorphic mask-side High-NA imaging to the instrument in 2015. Mask-side Hyper-NA EUV imaging is available to our users since 2024. We have qualified the imaging system and demonstrated imaging of 5-nm hp (wafer-scale) lines and spaces.

We will report the latest results of our mask-side Hyper-NA imaging program and discuss our plans for BEUV photomask imaging at wavelengths below 13.5 nm.

Presenting Author

Markus Benk is the lead scientist of the EUV Photomask Imaging Program at the Center for X-Ray Optics, Lawrence Berkeley National Laboratory. He received his diploma in photo engineering from the University of Applied Science Cologne in 2006 and his PhD in engineering from RWTH Aachen University in 2011. His research interests include sources, metrology, and optics for soft X-rays and extreme ultraviolet light.

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HVM-ready EUV zoneplate microscopy for mask defect review (Invited)

Luke Long, Christian Wilson, Matt Hettermann, Dave Houser, Chami Perera, Patrick Naulleau

EUV Tech Inc., Martinez CA, USA

With the increase in the number of semiconductor products manufactured with EUV lithography, so increases the need for cost-effective mask defect metrology. Zoneplate microscopy is a compact and cost-effective method that enables direct ultra-high magnification at-wavelength microscopy of EUV masks. A proven technique in soft X-ray synchrotron microscopy for decades, EUV Tech's stand-alone Actinic Image Review System (AIRES) proof of concept system has been operating in the field since 2020. In this paper, we present the next generation, HVM-compatible version of the AIRES platform. We discuss the innovations employed to overcome the intrinsic bandwidth requirements of zoneplate microcopy, focusing on throughput improvements that have been implemented in the next generation system. Additionally, we discuss advancements in pupil fill control that enable mask measurements using user-defined source profiles. Finally, we discuss novel imaging modalities enabled by facile swapping of the main zoneplate optic, namely the ability to use Zernike phase contrast imaging to view buried phase defects that may be otherwise difficult to discern from conventional imaging methods. These advancements are presented in conjunction with the latest imaging data from our HVM-ready tool, including wafer-print data demonstrating the correlation between the AIRES-measured aerial image and the realized on-wafer pattern.

P15

EXTREME ULE® for EUV Lithography reticles (Invited)

Roni Levi

Corning, Corning, NY

Increasing EUV source power levels to meet throughput targets, in combination with tightening overlay requirements, drives the need for substrate materials with enhanced thermal capabilities. While some of this thermal overlay can be compensated by the EUV scanner, improving reticle blank thermal properties is becoming critical for future high-power tools. Corning has traditionally produced material for ultra-stable optics using its CVD direct-to-glass process. This process delivers high quality, ULE® glass, which has become the Low Thermal Expansion Material (LTEM) of choice for EUV reticle substrates. This is mainly due to its thermal expansion behavior, but also extreme stability and other physical properties associated with a high purity silica-titania glass.
In this paper, we present a significant advancement in EUV reticle substrate performance. Corning's continuous investment in new technology is enabling significant advancements in EUV reticle substrate performance. EUV reticle substrates with significantly better thermal uniformity, can enable improved thermal behavior as needed in upcoming, higher power scanners. "Corning Extreme ULE® Glass" maintains the same high purity of the current ULE® glass ensuring the fundamental composition and physical properties, while delivering superior Tzc (Temperature at zero-crossing) uniformity.

Presenting Author

Dr. Levi earned a Ph.D. in Materials Science from Penn State University in 2009 and an M.Sc. in Chemical Engineering from the Israel Institute of Technology. Currently, Dr. Levi serves as the Semiconductors Technology Manager at Corning Inc. In this position, Dr. Levi focuses on developing a comprehensive understanding of the semiconductor industry roadmap, with a particular emphasis on advanced node lithography. They work collaboratively with Corning's partners and customers to devise innovative technical solutions that address key challenges in the semiconductor industry.
Prior to joining Corning, Dr. Levi worked at Intel Corporation from 2009 to 2017 as an etch development engineer within the Process Technology Development (PTD) group. During this period, they specialized in the development of new patterning processes crucial for Fin technology advancement. His research interests include low thermal expansion materials, thermal overlay, advanced EUV mask processes, and CMOS/DRAM transistor architecture.

P16

Ion Implantation for Improved Etching and Optical Performance in Next-Generation EUV Mask

Yunsoo Kim[1, 2], Dongmin Jeong[1, 2], Seungho Lee[1, 2], Myung-Jin Kim[3], Bom-Sok Kim[3], Taeho Lee[2] and Jinho Ahn[1, 2]

[1]Division of Materials Science and Engineering, Hanyang Univ.;
[2]CH[3]IPS (Center of Hyperscale, Hyperfunction, Heterogeneous Integration Pioneering Semiconductor Technology), Seoul, 04763, Republic of Korea;
[3]Radpion Inc., Daejeon, 34014, Republic of Korea

Extreme ultraviolet lithography (EUVL) is essential for advanced semiconductor manufacturing, but the limitations of tantalum (Ta)-based EUV masks necessitate alternative absorbers. However, many promising absorber materials face significant challenges in practical applications due to poor etchability during mask fabrication. In this study, we investigate ion implantation to enhance not only etching performance but also the imaging capability of next-generation EUV mask absorbers.

In our previous study, we explored platinum-tungsten (Pt-W) alloys to address etching challenges and confirmed their improved fabrication characteristics. To further enhance both etching and optical properties, we employed metal ion implantation, which can modify the microstructure and electronic band properties of EUV absorber materials. First, we optimized the optimal process conditions through simulations and experiments, and etching rate of Pt-W showed an approximately 1.4-fold increase, resulting in steeper sidewall angles in patterns. Additionally, we confirmed changes in the optical constants of Pt-W by combining X-ray reflectivity (XRR) and EUV reflectance measurements with Kramers-Kronig relations, while observing negligible impact on key film parameters such as thickness and surface roughness. These results demonstrate that ion implantation is a promising technique for enhancing both the etching performance and optical properties, thereby contributing to more efficient and precise EUV mask fabrication.

Presenting Author

Yunsoo Kim is a Ph.D. candidate in the Division of Materials Science and Engineering at Hanyang University under Professor Jinho Ahn. She received her Bachelor of Engineering in the same department in 2020. Her research focuses on next-generation EUV masks, particularly optical simulation and fabrication evaluation of mask absorbers.

P17

Holistic design for EUV blanks beyond 1.X nm node

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Through the thirty years' development period of EUV lithography, semiconductor industry solved its long-standing challenges such as blank defect and source power. Currently EUV lithography has reached high volume manufacturing.

Toward future technology node, new systems and materials are required for EUV lithography. For example, high NA EUV scanners are widely evaluated, and hyper NA system is investigated to achieve smaller pattern transfer.

EUV blank should also be updated its structure. The EUV blank is complex system which consists of many components such as reflective multilayer, cap layer, absorber and so on. In such a complex system, whole blank structure (not only one component) should be considered as a holistic system to meet all the requirements from blank, mask, and litho processes.

We have been developing whole new blank structures as a system. As alternative absorbers for Ta binary, low-n materials improve NILS and D2S. Nowadays, industry requires low-n and mid-k materials which enable wider process window. On the other hand, durable cap materials are needed since alternative absorbers largely change mask processes.

In this paper, we will report our development status of future EUV blank structures toward 1.X nm node and beyond.

Presenting Author

Yohei Ikebe joined HOYA Corporation in 2011. He was in R&D center and in charge of development of CVD 3C-SiC substrate. He joined the EUV development department in 2012. Currently, he is a manager related to film development for EUV blanks. He received BS degree and Ph.D degree in physics from university of Tokyo in 2008 and 2011, respectively.

P18

High NA EUV design to mask stitching enablement (Invited)

Kevin Lucas, Zac Levinson, Kai-Hsiang (Sean) Chang, Linghui Wu, Andy Dawes, James Ban

Synopsys Inc., Austin, TX 78746

In the last year anamorphic HighNA EUV lithography has become a reality. HighNA EUV scanners are exposing wafers for process, layout design and OPC/RET learning at multiple development fabs with more expected online soon. Leading design companies are also actively working on early physical design rules, memory/logic cells and place/route methods for HighNA EUV processes including the significant two-mask stitching challenges. Therefore, there is a strong need for design to wafer, stitching-aware HighNA EUV layout and mask optimization software. In this presentation we provide a detailed overview of HighNA EUV layout design, mask and wafer optimization flows and methods. We will provide examples of these methods applied to realistic physical designs, for different mask and wafer process options. We will also provide insight into how we see design-process flows and methods HighNA EUV lithography industry needs evolving in the next few years.

[1] Michael Lam, et. al. Computational Lithography Solutions for High NA EUV with Mask Stitching. EUVL Workshop 2024.

Presenting Author

Kevin Lucas received a B.A. in Physics from Univ. California Santa Cruz and a Ph.D. in Electrical Engineering from Carnegie Mellon Univ. In 1994 he joined Motorola APRDL working mainly on OPC, lithography simulation and design rules but also developed an EUV Mask topography simulator in 1997 for EUV LLC support. He joined Synopsys in 2006 where he is a Senior Architect working on HighNA EUV tools & flows. He is a Fellow of SPIE.

P19

Advanced Ion Source & Target Developments for EUV Mask Multilayer Deposition (Invited)

Katrina Rook

Veeco Instruments, 1 Terminal Drive, Plainview NY 11803

Mo/Si multilayers for EUV photomasks are deposited in a Veeco ion beam deposition (IBD) system. EUV mass-production has led the market to demand higher throughput and extended maintenance periods. Veeco is developing an upgrade package to meet this demand.

A larger ion source equipped with novel extraction grids has been demonstrated to increase Mo and Si deposition rates by 4-5x, resulting in a throughput improvement by 2.5x. The larger ion source also allows for a practical deposition rate at lower ion beam energy, mitigating Mo/Si intermixing, and improving reflectivity by 1%, as well as improving the cross-mask reflectivity uniformity. Furthermore, incidence angle tuning can improve both reflectivity (by 0.5%) and defectivity.

The IBD maintenance period is currently limited by defect performance over sputtering target life. The targets develop roughened surface areas and surface "nodules". To improve target erosion uniformity, we have developed a rotatable target assembly, as well as increased the target area by 40%. TEM observations reveal significant impact of target rotation on nodule morphology. Mo/Si EUV performance is maintained under either continuous rotation or indexed operation.

Presenting Author

Dr. Katrina Rook is Principal Process Engineer with the Advanced Deposition and Etch division of Veeco Instruments. Katrina has 35 years of experience in thin-film processing and characterization techniques. She received her MS and PhD in Physics from Carnegie Mellon University. Since 2017, she has been engaged in development of EUV mask-blank and EUV pellicle processes by ion beam deposition. For the presented material, Katrina expresses special thanks to her co-workers Dr. Mario B. Roque and Dr. Antonio Checco.

P21

High Resolution Imaging and Spectrographic Instruments for λ = 1-10 nm X-ray Astrophysics (Invited)

Mark L. Schattenburg

Space Nanotechnology Laboratory (SNL)
MIT Kavli Institute for Astrophysics
Cambridge, Massachusetts

The soft x-ray band (λ = 1-10 nm, E = 0.1-1 keV) is of great interest in astrophysics due to the copious line emission from hot, energetic objects such the accretion disks and jets of black holes and the debris from supernova explosions. For example, high resolution x-ray spectra of hot plasmas in the 1-10 million degree range can reveal the physics of these interesting objects. Our lab has developed a new type of high-resolution x-ray disperser called the critical-angle transmission (CAT) grating. A hybrid between transmission and reflection gratings, nanofabricated CAT gratings efficiently disperse soft x-rays into high diffraction orders demonstrating spectral resolving power ($\lambda/\Delta\lambda$) of over 12,000.
The Space NanoLab is also developing a new type of soft x-ray telescope that will have over 10^5 times higher resolving power than current x-ray telescopes such as the Chandra Observatory. This is based on extensions to the Wolter-Schwarzschild grazing incidence design that allow precise matching all optical path lengths through the telescope. From Fermat's principle, this would enable diffraction-limited imaging performance over meter-scale apertures, thus achieving micro-arc-sec imaging performance. This is high enough to directly image black holes such as the one at our galactic center.
We will discuss the status of CAT grating nanofabrication technology and show early work to fabricate and characterize diffraction-limited telescope mirrors using shear interferometry at visible and x-ray wavelengths.

Presenting Author

Mark Schattenburg is Senior Research Scientist at MIT and Director of the Space NanoLab. The SNL pioneered high resolution soft x-ray spectroscopy and provided nano-fabricated diffraction gratings for over 10 NASA missions. He was an early proponent of x-ray lithography and was awarded the BACUS prize for the development of the attenuated phase shift mask. He started two companies in the nanolithography space, the first (PGL, Inc) fabricates meter-scale diffraction gratings for laser fusion energy, the second (Lithoptek LLC) builds tools that dramatically improve CD control during EUV lithography.

P22

Absolute Traceable Electrical Substitution Radiometers for EUV Wavelengths and Beyond (Invited)

Brian J. Simonds, Bradley Pelz, Patrick McArdle, Jack Tanner, Chris Yung, Steve Grantham, Stephanie Moffitt, Rob Vest, John Lehman, Michelle Stephens

National Institute of Standards and Technology, Boulder, CO 80305 USA

The calibration of EUV radiation detectors to a primary standard is currently limited to between 1 nW and 10 µW, which falls well short of the nearly 1 kW produced by EUV lithography tools. In practice, this measurement gap is filled by engineering solutions requiring assumptions that adversely impact measurement uncertainty and reliability. NIST is developing a chip-based, primary standard electrical substitution radiometer capable of detecting up to 1 W of optical power that is deployable and operates at room temperature. This would extend the existing primary standard range by 5 orders of magnitude and would be useful for both EUV lithography and metrology inspection tools. For decades, the NIST Sources and Detectors Group has developed similar devices for the ultraviolet to THz regime. These microfabricated, fit-for-purpose devices are made solely in the NIST cleanroom and are currently being used as primary standards in our calibration facilities, on metrology satellites orbiting Earth, and elsewhere [1]. At visible wavelengths and power levels > 1 mW, experiments have shown that these devices are comparable to some classes of cryogenic radiometers, but at room temperature and with much faster response times [2]. In this talk, I will discuss the basics of these devices, how they compare to prior and existing radiometers, and the challenges we'll overcome to apply these devices to the EUV. I will also discuss possibilities for extending these devices to higher powers and shorter wavelengths.

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

[2] White et al., Decadal validation of the LASP TRF cryogenic radiometer by NIST, and establishment of a replacement room temperature standard, *Metrologia* **59** 065006 (2022)

Presenting Author

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

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Examining Kinetic Plasma Behavior in EUVL Sources with Particle-In-Cell Simulations

Kirill Lezhnin

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Laser-produced plasma from the interaction of CO_2 laser with a tin droplet serves as an EUVL source for advanced microchip manufacturing. Understanding the physics of EUVL sources is crucial for further advancements in nanolithography. Numerical simulations help in comprehending the interplay of multiple physics domains in these systems, with radiation hydrodynamics as the primary modeling approach. However, for hot, tenuous plasmas—such as the edge of an expanding tin plasma—its assumptions may break down. Recent studies [1] indicate that kinetic effects influence heat transport and laser absorption, necessitating advanced models to refine radiation hydrodynamic simulations. As part of the SparkLight Center initiative at Princeton Plasma Physics Laboratory (PPPL), we are developing the first-principles kinetic Particle-In-Cell code PSC to simulate expanding tin plasmas. Previously, we benchmarked PSC against the hydrodynamic code RALEF-2D [2]. Here, we examine tin plasma expansion into a background gas, comparing PSC with the hydrodynamic code FLASH. By varying gas pressure, we observe up to a 50% difference in peak tin ion energies between PSC and FLASH, underscoring the importance of kinetic effects for the accurate modeling of fast ion debris. Future work includes validating our numerical studies against experiments conducted at the SparkLight Center at PPPL.

[1] J. Gonzalez, J. Sheil, PRE (2025)
[2] S. R. Totorica, K. Lezhnin, D. J. Hemminga, J. Gonzalez, J. Sheil, A. Diallo, A. Hyder, W. Fox, APL (2024)

Presenting Author

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

P32

Plasma Simulations of EUV/x-ray Sources: Radiation Transport and Atomic Physics Models (Invited)

Igor Golovkin

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Prism Computational Sciences, Inc. uses state-of-the-art plasma radiation and atomic physics simulation tools for investigating radiation sources at short wavelengths for next-generation lithography systems. A suite of well-benchmarked radiation-hydrodynamics and spectral analysis codes can simulate the characteristics of radiation emitted from laser-produced plasmas (LPP). Prism's atomic and radiation physics simulation tools have been previously applied to the analysis of EUVL LPP experiments and have been shown to accurately predict the properties of source plasmas in Sn and Xe experiments. These properties include not only time-integrated conversion efficiencies, but also time-resolved in-band radiation. We will discuss key physics aspects of the simulations and present new results for soft x-ray sources produced by laser irradiation of N and Gd targets. We will highlight the importance of accuracy and completeness of atomic structure calculations and address possible effects of non-equilibrium atomic kinetics and non-local radiation transport.

Presenting Author

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

P33

Atomic model to model EUV emission spectrum and to produce the opacity table of tin (Invited)

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

[1]QST, Kizugawa, Kyoto, Japan
[2]ILE, The University of Osaka, Suita, Osaka, Japan
[3]Hiroshima University, Higashi Hiroshima, Hiroshima, Japan
[4]Hokkaido University, Sapporo, Hokkaido, Japan

We investigate atomic processes in tin plasmas for the extreme ultra-violet (EUV) source for microlithography, with the method applicable to model Blue-X sources. The collisional radiative model of tin has been extended [1,2] to include emission from multiply excited states [3], higher charged ions beyond 13+, and more 4-5 and 4-6 UTAs that appear in the shorter wavelength region (6-12 nm) to reproduce emission spectrum from high-density plasmas. The results are compared with the experimental spectrum [4]. We discuss the effect of opacity, including the modeling methods of evaluating the radiative transfer in the plasma, which would cause increased spectral width of the main peak at λ=13.5 nm in the solid-state laser-pumped plasmas.

[1] A. Sasaki, J. Appl. Phys. 107, 113303 (2010).
[2] A. Sasaki, Appl. Phys. Lett. 124, 064104 (2024).
[3] R. Schupp, et al. Phys. Rev. Appl. 12, 014010 (2019).
[4] Y. Pan, et al. Appl. Phys. Lett. 123, 204103 (2023)

Presenting Author

Akira Sasaki obtained Dr. Eng. from Tokyo Institute of Technology in 1991 and joined Japan Atomic Energy Research Institute, presently National Institutes for Quantum Science and Technology (QST), in 1996. He investigates the modeling of atomic processes and radiative transfer in the plasmas to investigate EUV spectrum. He has developed a collisional radiative model based on computational atomic data and using statistical methods. He has been involved in the research project for EUV lithography since 2003 for the analysis of emissions from tin sources. He is also interested in Blue-X sources as a future technology.

P41

Advanced BlueX Multilayer Coating Designs Strategies (Invited)

Vlad Liberman

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BlueX lithography system uses multilayer (ML) reflective optical elements for beam formation, photomask illumination, and optical projection. Direct ML design scaling from 13.5-nm EUV is challenging due to significant limitations of optical properties of existing materials at shorter wavelengths.[1] We will show results of optimization-driven ML designs based on extensive optical simulations for these wavelengths. We will discuss potential designs and strategies for overcoming these inherent material limitations that would lead to higher performing ML stacks.

[1] https://henke.lbl.gov/optical_constants/

Presenting Author

Dr. Vladimir Liberman received undergraduate degree in Physics from Princeton University and the Ph. D. degree in Applied Physics from Columbia University.

Since 1996, Vladimir Liberman has been a staff scientist at MIT Lincoln Laboratory, where he has worked on lifetime testing and evaluation of optics for advanced 193/157/121 nm lithographic applications as well as optical characterization of nanomaterials. He has been involved, both computationally and experimentally, with a wide variety of materials-related projects for sensing, light shaping and energy-harvesting applications.

P42

Beyond One-Size-Fits-All: Tailoring EUV (and BEUV) Optics for HVM Efficiency (Invited)

Donis Flagello

Nikon Research Corporation of America
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Extreme Ultraviolet (EUV) optics, and the subsequent exploration of Hyper-NA optics and Beyond EUV (BEUV) wavelengths, is characterized by an exponential surge in system complexity and manufacturing costs. The prevailing "one-size-fits-all" paradigm, wherein a single optical system is designed to pattern all critical integrated circuit features, leads to excessively intricate optical designs and formidable manufacturing challenges, especially for the optical systems. This universal approach is inherently inefficient, hindering the exploration of more streamlined and cost-effective alternatives.

We present a paradigm shift towards the development of specialized optical systems for high-volume manufacturing (HVM), tailored to specific subsets of pattern topologies such as dense lines with variable pitch. This reduction in overall system complexity is shown to result in optical designs with fewer and smaller mirrors, enhanced aberration control, and offers radically increased throughput without necessitating exorbitant source power requirements. In addition, our proposed solution offers some of the highest image contrast possible. We also assert that this specialized optical system strategy provides a viable pathway to substantially lower HVM costs, improved system stability and reliability. We believe that this strategy can lead to a more cost-effective and viable solution particularly critical for the successful implementation of future BEUV wavelengths.

Presenting Author

Donis Flagello has worked within the photolithography field and related optics industry for almost 45 years. He has worked in multiple areas that have spanned manufacturing, development and research fields. He has many publications and patents specializing in image formation, high NA imaging systems, polarization, immersion lithography, aberration and lens metrology, optical system modeling, EUV systems, and simulation. Donis is currently the President and CEO of Nikon Research Corporation of America, which performs research and development for all business units and divisions of Nikon. He holds a Ph.D. from the University of Arizona in Optical Science, and he is a Fellow of SPIE and Optica.

P43

Synthesis and metrology of Cr/Sc-based multilayer mirrors for the water window (Invited)

F. Delmotte[1], E. Meltchakov[1], A. Sokolov[2], P. Mercère[3], E. Gullikson[4]

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[2]Helmholtz-Zentrum Berlin, BESSY II, Berlin, Germany
[3]U. Paris-Saclay, Synchrotron Soleil, Gif-sur-Yvette, France
[4]Center for X-ray Optics, LBNL, Berkeley, California, USA

Cr/Sc-based multilayer mirrors for the water window have been studied and developed by several laboratories during the last 30 years for applications such as microscopy, attosecond science, X-FEL and synchrotron sources, semiconductor microanalysis and x-ray spectroscopy. However, the reported experimental peak reflectance is still far from the theoretical value, mainly due to the drastic influence of interfacial imperfections at these short wavelengths.
We have recently demonstrated high experimental peak reflectance at near-normal incidence near the Sc $L_{2,3}$ absorption edge (E≈399 eV) by experimental optimization of Cr/Sc-based multilayers [1]. We will report on the synthesis of these multilayer coatings, which consist of 500 periods with sub-nanometric individual layer thicknesses. In addition, we will show that the at-wavelength metrology of such multilayer mirrors raises some specific issues that have to be addressed. To do so, we will report on a comparative metrology study performed at 3 different synchrotron beamlines and discuss the main source of measurement uncertainties in this wavelength range.

[1] E. Meltchakov et al., "Optimization of Cr/Sc-based multilayer mirrors for water window soft x-rays", Optics Letter 49, 3420-3423 (2024)

Presenting Author

Franck Delmotte obtained a Ph.D. in Applied Science at the University Paris-Sud (Orsay, France) in 1998. He is Professor at the Institut d’Optique Graduate School (Paris-Saclay University, France) where he is teaching Optical Thin Films and X-ray Optics. As head of the XUV Optics Group at Laboratoire Charles Fabry, he has made fundamental contributions in short-wavelength optics, which enable many scientific and technological applications, from extreme ultraviolet (EUV) to X-rays: dual-band mirrors for solar physics, attosecond pulse compression by multilayer mirrors, broadband diagnostics for laser fusion (LMJ and NIF), innovative optics for next-generation X-ray sources, new multilayer interference coatings with several reflectivity world records. He was responsible for the development of multilayer optics for the two EUV telescopes and is co-Investigator of the ESA/NASA Solar Orbiter mission launched in 2020. He is currently leading a CNRS International Research Project in collaboration with the Center for X-ray Optics, Lawrence Berkeley National Lab and the Lawrence Livermore National Lab (California). In 2025, he was elected a Fellow Member of Optica.

P44

Hyper-NA: an EUV system with a numerical aperture of at least 0.75 (Invited)

Michael Patra

Carl Zeiss SMT GmbH,
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The current tools for EUV lithography are the NXE:3x00-scanners and EXE:5x00-scanners, with optical resolution limits of 13 nm and 8 nm half-pitch, respectively. Hence, the next logical step would be a generation of scanners approaching 5 nm half-pitch resolution limit. The most straightforward way is a further increase of the NA, where changes are largely confined to the scanner and a large part of the lithographic ecosystem can be used further.

This presentation will give an overview of Hyper-NA, i.e., an optical-lithography system with a numerical aperture (NA) of at least 0.75, so a significant step compared to the current NA of 0.55. For other quantities, such as wavefront quality and flare, the progress made in the past 15 years of EUV has been such that only moderately improvements are still needed in the future. While for Hyper-NA the mirror size will increase significantly compared to the EXE:5x00-scanner, the machine footprint will hardly increase, facilitating introduction in the fab.

The two risks most commonly mentioned in the context of increased NA are 3D-effects at the reticle and polarisation effects at the wafer. This presentation will describe these two effects and explain the proposed mitigation strategies.

Presenting Author

Michael Patra is system engineer and project manager for roadmap studies at Carl Zeiss SMT GmbH. He studied physics in Berlin, received his PhD in quantum optics from Leiden University, and was a Marie Curie fellow of the European Union, before joining Carl Zeiss SMT in 2006. Originally starting as illumination designer for DUV systems, he moved through different areas of SMT-R&D and currently holds more than 60 patents on different topics. Hyper-NA has been his main activity for the past five years.

P51

Advancing EUV Photoresist Development: High-Throughput Screening of Electron-Induced Chemical Transformations (Invited)

Oleg Kostko

Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Extreme ultraviolet (EUV) lithography has revolutionized semiconductor manufacturing by enabling further miniaturization of device features. However, developing high-performance EUV photoresists remains a critical challenge due to the complex interplay between photon- and electron-driven chemical reactions. While EUV photons initiate resist exposure, it is the subsequent electron-driven processes that primarily govern reaction pathways. A deeper understanding of electron-induced chemistry is essential for improving resist performance and patterning precision.

In this talk, I will present high-throughput methodologies designed to accelerate the screening of novel resist materials by rapidly evaluating their chemical transformations under EUV-relevant conditions. This approach involves in-situ electron emission and outgassing measurements during EUV exposure, where electron emission data provide insights into electron generation efficiency, and outgassing analysis reveals the products of photon- and electron-induced reactions. These advancements not only deepen our understanding of EUV resist mechanisms but also pave the way for the development of next-generation resist materials.

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.

P52

Isomorphic molecular control of Sb based inorganic EUV photoresist for optimized photosensitivity and stability (Invited)

Yeo Kyung Kang[1], Chan-Cuk Hwang[2], Myung-Gil Kim[1]

[1]Sungkyunkwan University, Suwon, Republic of Korea
[2]Pohang Accelerator Laboratory, Pohang University of Science and Technology, Pohang, Republic of Korea

Extreme-ultraviolet lithography (EUVL) is essential for advancing microprocessor and memory chip integration, surpassing the limitations of traditional photolithography. While inorganic EUV photoresists have been extensively researched, challenges persist, including low EUV sensitivity, limited understanding of photochemical mechanisms, and stability concerns. Notably, while antimony (Sb) carboxylate complexes exhibit high EUV sensitivity, their poor thermal stability hinders industrial adoption. This study explores the optimization of EUV sensitivity and stability through isomorphic control of Sb-based inorganic EUV photoresists. By manipulating the molecular geometry, we achieved a broad tuning range for EUV sensitivity (from 11 mJ/cm² to 220 mJ/cm²) and enhanced thermal stability up to 90 °C. Furthermore, homogeneous solid solutions of these molecular complexes demonstrated optimized EUV sensitivity and stability, accompanied by improved contrast.

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.

P53

Estimation of Resist Photospeeds for Blue-X Wavelengths (Invited)

Ralph R. Dammel

EMD Electronics

Inspection of the x-ray photoabsorption cross sections of tin at Blue-X wavelengths (6.7 nm, 3.4 nm, and 2.88 nm) shows that tin has very low absorption cross sections for all three wavelengths, which makes tin MORs a poor choice as a Blue-X resist. At the same time, chemically amplified resists are not expected to be able to achieve the required performance since they are limited by photocatalyst diffusion and have loitered at 12 nm HP final resolution for years. New resists will have to be developed for Blue-X, but it is difficult to estimate dose requirements without knowing resist composition and mechanism of action. This paper attempts to provide a new method of doing so.

A 2019 paper by B. Geh introduced an equation that related LCDU to incoming radiation dose and photon energy. This paper modifies Geh's equation in a way that specifically introduces resist absorbance as an additional parameter. This new modified Geh equation

$$LCDU = \frac{24}{\sqrt{\alpha d}} \frac{1}{NILS} \sqrt{\frac{hv}{D_i}} \qquad (1)$$

is first tested on data from 13.5 nm EUV lithography experiments and then used to compare exposure doses at 13.5 nm and Blue-X wavelengths using x-ray cross section data for these wavelengths. Even a lower bound estimate using the highest x-ray cross section of any element at the respective wavelength (see Table below) to indicate resist absorbance shows that exposure doses for resists in the water window region may be significantly slower than resists for 13.5 nm lithography. Combining these data with the known requirement for dose increase at lower CDs leads to the conclusion that Blue-X resists will be more than one order of magnitude slower than current 13.5 nm resists. It may well be that Blue-X lithography will require DSA rectification to achieve sufficient throughput.

Wave-length	α_2/α_1	$h\nu_1/h\nu_2$	D_{i1}/D_{i2}	Dose for tin resist @36 mJ/cm², 13.5 nm
2.88 nm	3.67	4.69	17.20	619
3.4 nm	3.40	4.00	13.61	490
6.8 nm	2.07	2.00	4.15	149
13.5 nm Sn	1.00	1.00	1.00	36

P54

Vapor phase metal-oxide infiltration for synthesis of positive-tone hybrid EUV resists

Nikhil Tiwale

Center for Functional Nanomaterials (CFN), Brookhaven National Laboratory (BNL), Upton, NY 11973, USA

Organic-inorganic hybrid resists are proving promising in meeting rigorous performance requirements of EUVL and many suitable negative-tone hybrid resist platforms have been reported.[1,2] However, the development of positive-tone hybrid resist system has lagged behind. We have pioneered novel ex-situ synthesis route for positive-tone hybrid resists using vapor phase infiltration of metal-oxides, exhibiting ultra-high etch selectivity for Si patterning and EUVL patternability.[3,4] We expand the approach to high sensitivity resist that can be developed in alkaline developer, realizing residue-free patterning accompanied by sensitivity improvement for both EBL and EUVL patterning. The talk will present recent experimental findings towards high-resolution line-space and contact-hole patterning using EBL/EUVL.

[1] Saifullah, Tiwale and Ganesan, JM3, **21**, 1 (2022)
[2] Saifullah, Tiwale et al. ACS Nano **18**, 24076 (2024)
[3] Tiwale, Nam et al. J. Mater. Chem. C **7**, 8803 (2019)
[4] Subramanian, Tiwale, Nam et al. Adv. Mater. Interfaces **10**, 2300420 (2023)

Presenting Author

Dr Nikhil Tiwale is Nanofabrication Research Staff (Assistant Scientist) in Electronic Nanomaterials Group at CFN-BNL. He pursued postdoctoral research working with Dr. Chang-Yong Nam at CFN-BNL, employing infiltration synthesis for developing hybrid resists for advanced nanolithography and fabrication of nano(opto)electronic devices. He obtained his PhD from University of Cambridge in 2017 on EBL direct-write ZnO nanodevices, under the supervision of Prof. Sir Mark Welland. Before joining BNL, he worked as silicon process engineer at Adaptix Ltd, a startup company developing portable X-ray sources for radiology.

P55

Organic-Inorganic Hybrid EUV Photoresists Derived from Atomic Layer Deposition Techniques (Invited)

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

[1]Center for Functional Nanomaterials, Brookhaven National Laboratory, Upton, NY 11973
[2]Department of Materials Science and Engineering, University of Texas at Dallas, Richardson, TX 75080

In this talk, I will present our recent progress in the vapor-phase synthesis of novel organic-inorganic hybrid EUV resists using atomic layer deposition (ALD) techniques—specifically, vapor-phase infiltration (VPI) and molecular ALD (MALD)—and discuss their electron beam and EUV patterning characteristics. VPI involves the infiltration of gaseous inorganic precursors into existing organic resists, while MALD utilizes the cyclic deposition of organic and inorganic moieties. Key findings from our work include: (1) the critical role of compatibility between infiltrated inorganic species and resist developers in VPI-derived resists, and (2) the correlation between 100 eV electron beam sensitivity and EUV sensitivity in MALD resists. If time permits, I will also provide a brief update on the DOE Accelerate Initiative project, "Angstrom Era Semiconductor Patterning Material Development Accelerator", as well as the ongoing development of an EUV interference lithography patterning end-station at BNL

Presenting Author

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

P56

Recent Developments and an Unexpected Discovery in Our Tin-Based Inorganic Molecular Resists for EUV Lithography (Invited)

Hyun-Dam Jeong

Chonnam National University, Gwangju, 61186, Republic of Korea

Our lab first introduced a novel non-alkyl tin-oxo cluster, designated as CNU-TOC-1(4C-C), in 2023. Its structural properties were characterized by small-angle X-ray scattering (SAXS), revealing a diameter of approximately 11.6 Å, and it has demonstrated promising potential for EUV lithography applications. In addition, in 2024, we found that the dose-to-size (DtS) performance could be improved by tuning its molecular structure. More recently, in 2025, we also identified that removing a specific impurity significantly enhanced its sensitivity to electron-beam and EUV exposure, and further demonstrated that fine-tuning the functional groups can additionally improve sensitivity. From these developments, we believe that the CNU-TOC-01(4C-C) cluster, with optimized formulation and process, holds great promise for future EUV lithography applications due to its inherent molecular structure. In the course of developing inorganic resist materials exhibiting a novel chemical contrast mechanism over the past five years, we discovered a previously unknown molecular structure (CNU-TIDO-AA) in March 2024, which is unprecedented in chemistry. Initial evaluations of this material were conducted in April 2024 using MET5, demonstrating promising performance. Our lab is currently investigating how this novel molecular structure (CNU-TIDO-AA) will impact the fields of inorganic EUV resists and semiconductor technologies, as well as exploring potential applications in other areas.

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).

P57

EUV photoresists with controlled sequences lead to improved stochastics and the discovery of a novel patterning mechanism

Chenyun Yuan

Ober group, Cornell University, Ithaca, NY, 14853

Stochastics are becoming a more critical issue as lithography moves more fully into the extreme ultraviolet (EUV) era. Chemical stochastics, a contributor to overall stochastics issues, is due to chemical inhomogeneities in photoresist molecular structures. In conventional polymeric photoresists, the inhomogeneities are in their molecular weight, composition, and sequence. In some cases, the unbound photoacid generator (PAG) molecules may not mix with polymers homogeneously on the nanoscale and add to stochastics. In this study, we identified a photoresist system based on polypeptoids, which can be synthesized with precise control over length, composition, and sequence through solid-phase submonomer synthesis. The polypeptoid photoresists are patterned in negative tone under either e-beam or EUV exposures without the need to add any photoactive compounds, to form a monomolecular system that significantly reduces chemical stochastics. We studied the underlying patterning mechanism by multiple characterization methods, and we believe the solubility is due to a mechanism rarely explored in EUV photoresist polymer design. We have studied the effect of composition and sequence on lithographic outcomes and found systematic trends. Using EUV exposure, the best resolution we achieved was 14 nm half-pitch.

Presenting Author

Chenyun Yuan is currently a 4th-year Ph.D. candidate in Materials Science and Engineering at Cornell University, under the guidance of Prof. Christopher Ober. Before embarking on his doctoral journey, Chenyun earned his B.S. degree from Cornell University in 2021. His research focuses on the development of sequence-defined polymeric materials tailored for photolithography applications.

P58

Next-Generation EUV Double Amplification Photoresists From Acid-Catalyzed Chain Unzipping (Invited)

Rachel Snyder

DuPont Electronics & Industrial, Marlborough MA

The technical demands for photoresists continue to evolve with the adoption of both low and high numerical aperture (NA) EUV technology. Photoresists that can achieve high resolution, rapid throughput driven by enhanced photosensitivity, and reduced film thickness are critical for advancing next-generation nodes. "Double amplification resists" (DARs) are an interesting class of resists that use a tandem acid-catalysis and depolymerization strategy to achieve fast photospeeds in EUV applications. Unlike conventional deprotection strategies, contrast is achieved by converting insoluble polymer into developer soluble monomers.

Here, we share our work developing a series of DARs from polyphthalaldehyde derivatives and assess their performance against traditional chemically amplified resists (CARs). We will discuss the unique advantages and challenges for DARs using insights from KrF and E-Beam lithography. Lastly, we will share our recent progress in optimizing DAR formulations and processing for EUV patterning.

Presenting Author

Dr. Rachel Snyder is a Lead Scientist at DuPont Electronics & Industrial in Marlborough, MA. She completed her graduate work with Professor Geoff Coates at Cornell University, where she gained expertise in polymer design, synthesis, and characterization for improved sustainability. In August 2021, Rachel joined DuPont in Marlborough in the Emerging Technologies Group and worked on photo-patternable optical materials for display applications. She joined in the Lithography group in February 2024 and is currently the program manager for the Next-Generation EUV Photoresists program.

P59

EUV NTD-CAR performance toward high-NA EUVL

Nishiki Fujimaki[1], Hironori Oka[1], Waut Drent[1], Arjun Singh[1], Keiyu Ou[2], Keita Kato[2], Naohiro Tango[2]

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Since 2019, Extreme Ultraviolet (EUV) lithography has been deployed for high volume manufacturing of advanced CMOS technologies. However, feature size uniformity and defectivity of EUV chemically amplified resist (CAR) materials has been limited by stochastic issues, especially photon shot noise in EUV aerial images and chemical stochastics in photoresist formulations. Additionally, EUV mask designs have mostly been limited to darkfield layouts because higher absorber coverage area is required to mitigate EUV mask blank defects. EUV exposure of specially formulated CARs with negative tone development (NTD) has shown promise in terms of improving feature size uniformity and allowing direct printing of tone inverted features [1]. New chemical designs were introduced, such as new types of absorption units to mitigate photon stochastics, and new types of photo acid generators (PAG) connected to photo decomposable quenchers (PDQ), called PCP in short, to mitigate chemical stochastics. Also, the use of a new NTD developer was found to be effective in improving both pattern collapse and nano-bridge defects by suppressing swelling. In this talk, the latest lithographic performance will be reported with various features and applications toward high-NA EUV lithography will also be discussed.

[1] "Exploring stochastic reduction and lithographic performance by using EUV CAR-NTD", SPIE proc. 13428-18 (2025)

Presenting Author

Nishiki Fujimaki, is a researcher of FUJIFILM Corporation and is currently assigned to imec.

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 R&D of photoresist materials and process technology.

P60

The Multi-Trigger Resist - EUV Performance Update (Invited)

C. Popescu, G. O'Callaghan, A. McClelland, C. Storey,
A.P.G. Robinson

Irresistible Materials, The Science Centre, Wolverhampton Science Park, Wolverhampton, UK
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Novel resist materials are required to support the on-going improvement of EUV lithography. Resolution, roughness and dose requirements will continue to become more severe. In addition, depth of focus will be significantly reduced with the move to High-NA, necessitating reductions of the thickness of both resist and underlayer, and in turn the need for increased EUV photon absorption and etch durability, to enable viable patterning and pattern transfer.
Irresistible Materials (IM) is developing novel resists based on the multi-trigger concept. The mutli-trigger resists are negative-tone organic molecular materials, based on cationic ring opening polymerization. In a multi-trigger resist (MTR) multiple elements must be simultaneously activated to enable the catalytic reaction. Chemical contrast and resolution are therefore enhanced due to a dose dependent intrinsic quenching behaviour, and MTR shows good lithographic results and wide flexibility.
Here we present recent progress with the MTR. Pitch 28 L/S patterning is demonstrated at 50 mJ/cm^2, with 105nm focus margin. Larger pitch L/S patterning with low roughness and a sub-30mJ/cm^2 dose, suitable for double patterning applications has been investigated. P32 pillars, with 2.5 nm LCDU, and low dose (<40 mJ/cm^2) and p32 contact hole patterning has also been demonstrated.

Presenting Author

Alex Robinson is co-founder, and Chief Technical Officer of Irresistible Materials Ltd, which is developing materials to support EUV lithography.

P61

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

Anuja De Silva

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Aether® dry resist deposition and development technology has been adopted for high volume manufacturing to break the tradeoffs among resolution, sensitivity, roughness, and defect performance with full productivity entitlement of 0.33NA EUV lithography. 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 bright field contact holes will be presented showing the readiness towards the high NA EUV patterning. Initial high NA data with P18/16L/S and small tip-to-tip structures with lower variability will demonstrate dry resist capability to realize the potential of HNA EUV patterning. 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 for high NA patterning will also be discussed.

P62

Advanced Coater/developer Technologies for High-NA EUV Lithography (Invited)

Cong Que Dinh

TEL Technology Center, America, LLC

Improvements in EUV patterning performance by optimizing CAR and MOR coater/developer processes to meet the requirements of high-NA EUV lithography in mass production will be discussed. We will also discuss the challenges and the solutions of those processes in high-NA EUV lithography.

Presenting Author

Dr. Dinh is currently an expat in TEL Technology Center, America, LLC in Albany, New York. Before this position, he was a lithography senior specialist at Advanced Technology Department in Tokyo Electron Kyushu, where he was working on development of track processes for next generation lithography. Prior to 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.

P63

Amorphous Zeolitic imidazolate Framework (aZIF) Films for Electron Beam, Extreme UV, and Beyond Extreme UV Lithography Applications (Invited)

Michael Tsapatsis

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Amorphous zeolitic imidazolate framework (aZIF) films have been recently introduced as resists for electron beam and extreme ultraviolet lithography (EBL and EUVL). In this talk aZIF film performance will be discussed comparing liquid and vapor phase deposition and dissolution/etching processing. A spin coating method for depositing aZIF films with controllable thickness using dilute precursors mixed immediately before encountering the substrate will be presented and the film quality obtained by this Chemical Liquid Deposition (CLD) method will be compared with films deposited by vapor phase Molecular Layer Deposition (MLD). Liquid phase dissolution fundamentals for these resists will be discussed, and development in solvents will be compared with vapor phase etching. The ability to combine liquid and vapor phase deposition and etching processing steps to improve resist performance and accelerate the discovery of resist formulations will be demonstrated. EUV and BEUV performance characteristics will be presented for amorphous zinc 2-methyl-imidazolate films and other metal-imidazolate formulations.

P64

Lab-based EUV interference lithography for large-area nanopatterning towards sub-10 nm resolution (Invited)

Sascha Brose[1,2], Lars Lohmann[1], Annika Bonhoff[1], and Carlo Holly[1,2]

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The presented exposure tool utilizes partially coherent radiation from a compact discharge-produced plasma (DPP) EUV source, operated either at an exposure wavelength of 10.9 nm or at 13.5 nm fulfilling different exposure requirements. Large area patterning of nanoscale structures up to several cm² is carried out at an exposure wavelength of 10.9 nm by operating the source with an argon/xenon gas mixture [1]. For the characterization of EUV photoresists at 13.5 nm main exposure wavelength, the source is operated with pure xenon and spectrally filtered by a customized multilayer mirror [2]. For partially coherent radiation as provided by the DPP source, the (achromatic) Talbot lithography has proven to be most suitable with a demonstrated resolution in the sub-30 nm regime. To further scale down the resolution towards the sub-10 nm regime efficient phase-shifting transmission masks need to be designed and fabricated [3]. Different material combinations and geometries can be applied to enable highest contrast of the resulting intensity distribution on the wafer [4]. The latest advancements in both simulation and fabrication processes for high-resolution phase-shifting masks along with achieved exposure results are presented in this contribution.

[1] S. Brose et al., J. Micro/Nanolithogr. MEMS MOEMS 15(4), 043502 (2016)
[2] B. Lüttgenau et al., Appl. Opt. 61(11), 3026-3033 (2022)
[3] S. Brose et al., Proc. of SPIE 10450, 104502A (2017)
[4] B. Lüttgenau et al., J. Micro-Nanopattern 23(4), 043002 (2024)

Presenting Author

Dr. Sascha Brose received his Ph.D. degree in mechanical engineering in 2019 from RWTH Aachen University and is group manager of the research group "EUV Technology" at the Chair for Technology of Optical Systems (TOS) at RWTH Aachen University. Since 2009 he has been working in the field of extreme ultraviolet applications with focus on the conceptual design, functionalization, and operation of EUV tools for high-precision metrology and nanoscale patterning. His research fields include EUV lithography, EUV metrology, and material modification by focused EUV radiation. Additionally, he is an expert in micro- and nanofabrication processes of optical components especially designed for EUV wavelengths. He has authored and co-authored more than 40 scientific publications.

P65

EUV Lithography at The Center for X-Ray Optics (Invited)

Bruno La Fontaine

Center for X-Ray Optics, Lawrence Berkeley National Lab,
1 Cyclotron Road, Berkeley, CA 94720, USA

The Center for X-Ray Optics (CXRO) has a long history of important contributions to the development of EUV lithography. As High-NA EUV is being introduced in manufacturing, we are transitioning our research activities to address the challenges that need attention going forward: understanding fundamental processes in resists, preparing for a hyper-NA EUV micro-exposure tool, and evaluating materials and masks for shorter wavelength lithography. We will provide a perspective on the most critical problems to address and report on our progress toward these goals.

Presenting Author

Bruno La Fontaine is a senior scientist at Lawrence Berkeley National Laboratory and serves as the director of the Center for X-Ray Optics.

P66

Replacing EUV with X-ZPAL (Invited)

Henry I. Smith

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With the advent of free-electron lasers, capable of delivering high-intensity, collimated radiation at 4.5 nm wavelength, EUV lithography can be replaced with a maskless system that employs an array of transmissive diffractive Fresnel microlenses, in conjunction with a soft-x-ray-compatible modulator. The virtues of such a system, called X-ZPAL, include: focal-spot writing, which avoids troublesome interference effects; efficient focusing; operation in a He atmosphere for improved thermal control; utilization of carbonaceous resists for improved performance; and microchip innovations such as customization and eliminating counterfeit chips via encoding at the transistor level. The advantages of maskless soft-x-ray lithography over the many electron-based maskless schemes that have been pursued in the past will be described.

Presenting Author

Henry I Smith is Emeritus Professor at MIT and President of LumArray, Inc. He, his student and coworkers have contributed a number of innovations to nanoscale science and engineering, including: x-ray lithography, the phase shift mask, the attenuating phase shifter, achromatic interference lithography, zone-plate array lithography, interferometric mask alignment and graphoepitaxy.

P67

Development of a Next-Generation Interference Lithography End Station at the Swiss Light Source (Invited)

Iacopo Mochi

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https://www.psi.ch/en/lxn

Following the upgrade of the Swiss Light Source, a new interference lithography end station is under development to exploit the high brightness of the new synchrotron's beam and to push beyond the 5-nm half pitch limit we demonstrated lately[1]. The new system is designed as a successor of our old exposure tool and will benefit from 20 years of experience and lessons learned. It will also feature multiple and more flexible techniques including grating and mirror-based interference lithography, direct writing with focused and Bessel beams and EUV holography. In this paper, the critical features implemented to mitigate vibrations and thermal drifts will be outlined. The paper will also describe the target resolution limit for each of the different writing modes and it will present the timeline for the tool availability to the users.

[1] Giannopoulos at al. "Extreme ultraviolet lithography reaches 5 nm resolution" *Nanoscale*, 2024,16, 15533-15543

Presenting Author

Dr. Iacopo Mochi started working on EUV mask inspection at Lawrence Berkeley Laboratory in the Center for X-Ray optics. He operated the SEMATECH AIT, an EUV microscope for mask review. He later worked on the design and development of SHARP, an advanced EUV mask review tool that is currently operating at the Advanced Light Source in Berkeley. Subsequently, Dr. Mochi worked as an EUV mask R&D engineer at IMEC on the topic of sub-resolution assist features. He is currently a staff scientist and the group leader of the Advanced Lithography and Metrology group at the Paul Scherrer Institute.

P71

Increment of EUV radiation and reduction of ion energy of laser-produced Sn EUV-light-source plasmas by controlling initial plasma structure using multiple pre-pulse laser irradiations (Invited)

Kentaro Tomita[1], Yiming Pan[1], Hirokazu Hosoda[2], Shinji Nagai[2], Atsushi Sunahara[3,4], Katsunobu Nishihara[4]

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[2]Gigaphoton Inc., 400 Yokokurashinden Oyama,Tochigi, 323-8558, Japan
[3]Center for Materials Under eXtreme Environment (CMUXE), School of Nuclear Engineering, Purdue University, 500 Central Drive, West Lafayette, IN 47907, United States of America
[4]Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, Osaka, 565-0871, Japan

In EUV light sources for lithography, the challenge is to achieve both improvement of the conversion efficiency (CE) and reduction of debris, i.e., reduction of average kinetic energy of emitted ions. Toward this purpose, various types of the initial target shaping, that is, the preliminary laser irradiation, and the main laser irradiation conditions, have been investigated. However, there is no example of simultaneous measurement of CE and ion energy values and the physical quantities that determine them (CE and ion energy), namely, electron temperature and density, which are directly related to the radiation transport coefficient, and the spatial gradient of electron pressure, which forms the ion acceleration field.

In this study, we measured them together and revealed that another laser pulse (second pre-pulse) irradiated before the main laser pulse on the shattered tin target generated by the preliminary laser pulse (first pre-pulse) has a significant effect on the plasma state, resulting in a significant change in CE and ion energy.

Presenting Author

Kentaro Tomita received B. S., M. S., and Ph. D. degrees from Kyushu University, Japan, in 2002, 2004, and 2014, respectively. In November 2006 he was appointed Research associate at Kyushu University and became Assistant Professor in April 2007 at the same university. He became Associate professor in July 2020 at Hokkaido University, Japan. He is engaged in research of laser-aided diagnostics of industrial plasmas such as laser produced plasma for extreme ultra-violet light sources, atmospheric-pressure non-equilibrium plasma, arc discharge plasma, etc., which are produced under high pressure.

P72

Plasma Dynamics and Future of LPP-EUV Source for Semiconductor Manufacturing IV (Invited)

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

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[3]Division of Quantum Science and Engineering, Graduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-ku, Sapporo, Hokkaido 060-8628, Japan.
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[6]Utsunomiya Univ., 7-1-2 Youtou, Utsunomiya-shi, Tochigi 321-8585, Japan
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In this conference, we will report about new EUV research activities in Kyushu-Univ. in Japan. At the conference, we will report the latest research plan for challenging higher power EUV source

1. EUV Photon
The first topic is a new EUV exposure research center named "EUV Photon Co. This organization will support material development of the material industry of EUV lithography, for example photo-resist, photo mask, and so on. We have prepared EUV light source, exposure optical system, and vacuum chamber system for this exposure. In this presentation we will report the latest preparation of this organization.

2. EUV Source Research Program
The second topic is the new high power EUV source research program which has been being prepared in Kyushu-University. Since 2003, we have corroborated EUV source research with Gigaphoton. We are a pioneer of combination of pulsed CO2 laser and

Sn droplets, dual wavelength pico second laser pulses for shooting and debris mitigation by magnetic field have been applied. We have demonstrated high average power >300W EUV power with CO2 laser more than 27kW at output power in cooperation with Gigaphoton and Mitsubishi Electric up to now 2).

3. Thin Plasma Dynamics Measurement

The third topic is about the Sn plasma dynamics which dominate the EUV emission by using Thomson Scattering (TS) measurement. Last year our group announced the possibility of 10% conversion efficiency with simulation and experiment (fig.3). These results mention that there is still sufficient potential to increase EUV output power and conversion efficiency in the near future.

[1] Hakaru Mizoguchi, Kentaro Tomita, Daisuke Nakamura, Yukihiro Yamagata, Takeshi Higashiguchi, Atsushi Sunaha-ra, Katsunobu Nishihara, Takashi To-shima, Hiroki Kondo, Takuji Sakamoto, Tanemasa Asano and Masaharu Shira-tani: ” Plasma Dynamics and Future of LPP-EUV Source for Semiconductor Manufacturing II” SPIE 13215-63 (2024) .
[2] Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Krzysztof M. Nowak, Ya-sufumi Kawasuji, Hiroshi Tanaka, Yukio Watanabe, Tsukasa Hori, Takeshi Ko-dama, Yutaka Shiraishi, Tatsuya Yanag-ida, Tsuyoshi Yamada, Taku Yamazaki, Shinji Okazaki, Takashi Saitou.:” Per-formance of 250W High Power HVM LPP-EUV Source”, Proc. SPIE 10143, Ex-treme Ultraviolet (EUV) Lithography VIII (2017)
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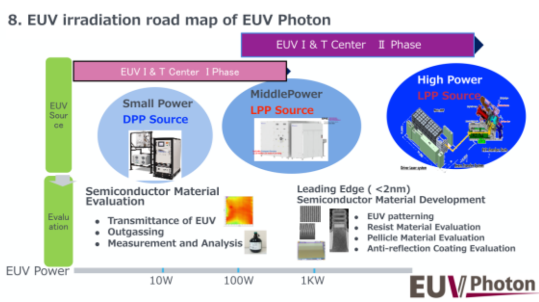

Fig. 1 Exposure Road Map of “EUV

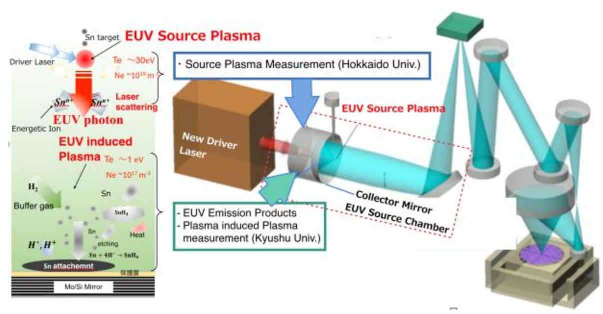

Fig.2 Higer power EUV Source Investigation in Kyushu Univ.

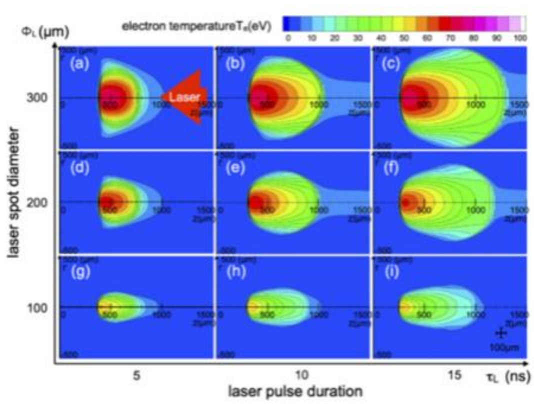

Fig.3 EUV Plasma simulation predict >10% conversion efficiency [3)]

Presenting Author

Title/ Position: Guest Professor of Kyushu University. (He was Senior Fellow of Gigaphoton Inc.)

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

P73

The path towards 1.5kW EUV with the CO2 drive laser (Invited)

Jens Brunne

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The CO2 drive laser has been pivotal in the industrialization of the EUV source, leveraging the high conversion efficiency of the 10µm wavelength alongside reliable, established laser technology. This contribution will highlight the key development milestones of CO2 drive laser technology, starting from its HVM market introduction in 2019, through the transition to 1µm Prepulse, and leading up to our current advancements. These include an overhaul of the core of our technology, the CO2 amplifier itself. This will enable a substantial efficiency boost, resulting in a significant power increase to the 1.5kW EUV regime, all within the same system footprint.

Presenting Author

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

P74

Diagnostics of Laser-assisted Discharge Tin Plasma EUV source using collective Thomson scattering

Hideyuki Sera[1,2], Akihisa Nagano[1], Yiming Pan[2], Kentaro Tomita[3]

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[2]Division of Quantum Science and Engineering, Graduate School of Engineering, Hokkaido University, Hokkaido, Japan

We have developed and operated a high-brightness EUV light source using laser-assisted discharge tin plasma (LDP) for actinic mask inspection in the semiconductor industry field. In EUV light sources using tin plasma, the emission intensity of a 2% bandwidth at a wavelength of 13.5 nm is determined by electron temperature and electron density. We have measured the electron temperature, density, and flow velocity field of the LDP EUV source using collective Thomson scattering technique. As far as we know, it is for the first time to measure the plasma parameters and the temporal behavior of the LDP from the laser injection to the end of the Z-pinch. As a result of the measurement, the plasma had an electron temperature of 21 eV and an electron density of 3×10^{24} m^{-3} at the timing when the EUV energy monitor signal was at its maximum, which was consistent with the results of the atomic modeling studies for high EUV emission region.

Presenting Author

Hideyuki Sera is a Chief Engineer at Ushio Inc. He joined the company in 2015 after completing his Master's degree at Keio University in Physics. He has been involved with measurement system using lasers and has served as the laser module owner for EUV light sources. Currently, he works as an R&D scientist focusing on EUV light source development.

P75

The Must Light Source

Yosuke Honda

High Energy Accelerator Research Organization (KEK)

Energy-Recovery Linac (ERL) based Free-Electron Laser (FEL) has been a promising solution for the high-power EUV light source for future semiconductor lithography. Considering the increasing demands of semiconductors and the roadmap for smaller nodes, realization of a higher power EUV (and BEUV) light source at high efficiency has been strongly required. At KEK, we have been designing ERL-EUV-FEL based on our experience of construction and operation of a test ERL accelerator. We will present the design of the accelerator system and its expected performance from the basic principle. It will explain the technical key items in the accelerator development planned in the next 5 years.

Presenting Author

Yosuke Honda received his PhD from Kyoto university in 2004. He is an associate professor of the High Energy Accelerator Research Organization (KEK). He belongs to the Innovation Center for Applied Superconducting Accelerators (iCASA). He has been working for accelerator science, especially in the interdisciplinary area of high quality electron beam and photonics.

P76

A compact laser-driven short-wavelength radiation source (Invited)

Yusuke Teramoto[1], Paolina Noll[1], Andrei Karabanov[1], Nurbaity Dziyauddin[1], Guido Mertens[1], Ralf Kops[1], Margarete Kops[1], Wilko van Nunspeet[1], Marcel Schneider[1], Johannes Ebert[2], Jochen Vieker[2], Klaus Bergmann[2]

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[2] Fraunhofer ILT, Steinbachstrasse 15, 52074 Aachen, GERMANY

Short-wavelength radiation sources, such as EUV sources, are used in various fields, especially in the semiconductor industry. The applications are broad and emerging as the semiconductor manufacturing technologies are evolving. Ushio, in collaboration with Fraunhofer ILT, has developed the laser-assisted discharge-produced plasma source (LDP source). The LDP source is used for mask inspection and sample exposure applications. We are also developing a compact laser-produced plasma source (LPP source) for applications that utilize a small emission volume, such as metrology applications. In its small form factor, the source employs a liquid metal-coated rotating disc target to generate EUV light by irradiating it with a focused pulse laser.

In 2024, we started contributing to the research project "XProLas." The project is supported by Germany's Federal Ministry of Education and Research (BMBF) to realize a high-brightness X-ray radiation source utilizing a high-intensity laser with industrial and academic partners. In the project, we use various lasers and liquid metal fuels to develop and evaluate the target system for the final project goal. EUV and shorter wavelength regions are used to evaluate the target performances. In this presentation, we will present the characteristics of the compact LPP source under various conditions.

Presenting Author

Yusuke Teramoto received Ph.D. degree in 2002 from Kumamoto University, Japan. He joined Ushio Inc. in April 2002 and started research and development of Xe- and Sn-fueled discharge-produced plasma (DPP) EUV sources. Since 2008, his R&D activities have focused on high-power and -brightness EUV generation from laser-assisted DPP (LDP) source, and high-brightness compact laser-produced plasma (LPP) source.

P77

Efficient EUV/B-EUV sources by laser irradiation schemes (Invited)

Takeshi Higashiguchi
Co-authors: Kazuyuki Sakaue, Daisuke Nakamura, Weihua Jiang, Atsushi Sunahara, Shinichi Namba, Padraig Dunne, Gerry O'Sullivan, and Eiji J. Takahashi

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We report on some approaches for efficient 13.5-nm EUV sources, with improving spectral purity (spectral efficiency) and suppressing the charge-states and kinetic energy of the fast ion debris. Recently, we have shown the efficient EUV source potential by controlling the electron density gradient of the pre-plasma and CO2 laser pulse duration [1]. We also demonstrated the conversion efficiencies of 4.7%-5% by multiple pulse irradiation experimentally, one of the highest values ever reported, in the case of a 1-μm solid-state laser-produced planar Sn target plasma by multiple laser pulse irradiation [2]. We show the B-EUV spectral narrowing for the B-EUV multi-layer mirror matching with the bandwidth of 0.6% at 6.76 nm [3] and the angular distribution separation with the ionic debris energy suppression by cross-laser-beam configuration [4]. Finally, we show the recent results for the water-window soft x-ray source experiments [5] as the next feasibility, such as "Blue-X" [6].

[1] A. Sunahara, A. Hassanein, K. Tomita, S. Namba, and T. Higashiguchi, Opt. Express **31**, 31780 (2023).
[2] T. Sugiura, H. Yazawa, H. Morita, K. Sakaue, D. Nakamura, E. J. Takahashi, A. Sunahara, G. O'Sullivan, S. Namba, and T. Higashiguchi, Appl. Phys. Lett **125**, 034103 (2024).
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[5] T. Soramoto, A. Ogiwara, H. Morita, W. Jiang, K. Sakaue, T. Ejima, G. O'Sullivan, S. Namba, and T. Higashiguchi, Opt. Lett. **49**, 5791 (2024).
[6] V. Bakshi, *EUV Roadmap Needs Extension*, EE Times (2018); https://www.eetimes.com/euv-roadmap-needs-extension/

Presenting Author

Takeshi Higashiguchi is a professor. He received his Ph.D. in engineering from Utsunomiya University. His research activities have focused on short-wavelength extreme ultraviolet (EUV & B-EUV at 6.*x* nm) and water-window soft x-ray sources, laser-plasma interaction, compact high-repetition rate thin-disk lasers, supercontinuum source, vector beam generation and determination of the polarization-state, and medical applications.

P78

Enhancement of spectral performance in gadolinium-based BEUV sources

Jingquan Lin

Changchun University of Science and Technology, China

Gadolinium laser-produced plasma (Gd-LPP) represents a promising BEUV lithography light source for future semiconductor manufacturing. In this study, a dual laser pulse scheme was firstly implemented to achieve a narrow spectral peak with an improvement of spectral purity[1]. Radiation hydrodynamics simulations revealed that the improved spectral purity stems from a flatter density gradient at the ablation front and a lower average electron density in the EUV emission region. Moreover, we seek to further enhance the Gd-LPP spectral performance by integrating a cavity-confined target with the existing dual-pulse laser scheme[2],and a maximum of 4.35% around 6.7nm at a pre-main pulse delay of 40 ns was achieved. Our findings offer an approach for enhancing spectral performance by optimizing the pre-formed plasma in a dual pulse scheme.

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[2] Zhilin Wen et al., Optics Express, 33, (2025) 8806

Presenting Author

Dr Jingquan Lin currently is a professor at Department of Physics, Changchun University of Science and Technology, China. His interest mainly focuses on the LPP source for EUVL. In his early career, he used to join the AIST, Japan to preform EUVL source research under consortium of EUVA & MIRAI project. After that, he moved to Germany to perform EUV mask blank defect inspection under the support by the European Union project "More Moore".

P79

SXR development for metrology, inspection, and process control using a discharge-produced plasma source (Invited)

David Reisman[1], Daniel Arcaro[1], Nick Lubinsky[1], Wolfram Neff[1], Kosuke Saito[2], Mike Roderick[1], Aaron Feldman[1], Henry Chou[1], Don McDaniel[1], Debbie Gustafson[1]

[1]*Energetiq Technology, Inc., Wilmington, MA 01887, USA*
[2]*Hamamatsu Photonics K.K., Japan*

Energetiq Technology's EQ-10 Electrodeless Z-Pinch™ EUV light source uses a xenon plasma Z-pinch to produce 13.5 nm (±1% BW) radiation with an EUV power of ~20W. Recently, we have developed a next-generation EUV source called "EQS-10," which enables an EUV power of >40W. Using the higher energy-per-pulse capability of this system, we are able to explore the use of different gases for shorter wavelength radiation. The most notable of these gases is nitrogen for 2.88 nm SXR radiation. Such a source can potentially be used for non-destructive inspection and metrology of 3D-stacked chip architectures. In this talk, we will present various designs to achieve appreciable SXR radiation. Specifically, we use radiation-MHD code calculations to explore the development of the Electrodeless Z-Pinch as an SXR source. Experimental data and their comparison to simulation results will be presented.

Presenting Author

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

P80

Laser-driven x-ray generation for industrial applications (Invited)

Jochen Vieker, Klaus Bergmann, Johannes Maximilian Ebert, Sarah Klein, Martin Traub, Rolf Wester, Stephan Herman Wissenberg and Hans-Dieter Hoffmann

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jochen.vieker@ilt.fraunhofer.de

Novel photonic applications require x-ray sources that surpass the limitations in brilliance and photon flux of classical electron beam driven x-ray sources. Laser-driven sources are considered as a next step to deliver high spectral brilliance from a Kα-line emission for analytical applications as well as highly energetic bremsstrahlung which may allow for imaging applications of thick, complex and high-Z materials.

Fraunhofer ILT is launching a new facility, dedicated to laser and application development for secondary sources of ionizing radiation.

The talk will focus on early results, such as optics layout and system architecture of laser-driven hard x-ray sources and applications, being in development in consortia projects. In these projects, several interrelated things are being considered, such as:

- application requirements on photon energy, brilliance, flux, bandwidth…
- light-matter interaction, such as pre-plasma effects and x-ray generation
- kW-class drive laser and pulse compression to 0.1-1 TW peak power
- beam delivery, pre-pulse and high-NA focusing to 10^{18}-10^{19} W/cm²
- regenerative target technology for continuous operation
- protection of optics against plasma, droplets, or fast ions
- Radiation safety

Presenting Author

Jochen Vieker received his Master in physics in 2011 from Bielefeld University, for his work on high harmonic generation. Since then, he has been scientist in the EUV technology group at the Fraunhofer Institute for Laser Technology ILT and finished his PhD in physics in 2019 at RWTH Aachen University for his research on power and lifetime scaling of discharge based EUV sources. As senior engineer and project leader he contributes to the fields of EUV technology and laser-driven secondary sources of ionizing radiation and applications.

P81

2µm fiber laser systems for next generation EUV plasma sources (Invited)

Dr. Christian Gaida

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

The semiconductor industry demands higher EUV power to increase wafer throughput and improve manufacturing efficiency as chip features shrink to ever-smaller nodes. Current CO_2 driving laser technology for EUV lithography faces challenges such as limited power scalability, low wall-plug efficiency, significant heat management issues, and complex system integration, all of which impact overall EUV source performance and cost-effectiveness.

Recent experimental and theoretical studies have identified the 2 µm wavelength range as a highly promising spectral region for driving EUV sources based on tin plasma emission [1,2]. The key reasons are: A) the conversion efficiency towards the EUV is on par with that achieved with CO_2-lasers; B) short-wavelength mid-infrared wavelengths can be emitted by solid-state lasers, which offers not only advantages in terms of efficiency and power scalability but also a lower complexity, cost and system foot-print; C) due to the shorter laser wavelength, the etendue of the plasma emission can be better than that achieved with CO_2-drive-lasers.

This presentation will introduce a concept for a 2 µm solid-state drive laser utilizing Thulium-doped fiber amplifier technology. It will also review the current advancements at TRUMPF Laser SE in performance scaling of Thulium-doped fiber lasers and explore their future potential. The findings pave the way for next generation drive lasers with unprecedented system foot-print, wall-plug efficiency (>15%), and EUV power (>1kW).

[1] Y. Mostafa, et.al., "Production of 13.5 nm light with 5% conversion efficiency from 2 µm laser-driven tin microdroplet plasma," Appl. Phys. Lett. **4** 123 (23), 234101 (2023).
[2] S. Langer, et.al., "Simulations of laser driven EUV sources—the impact of laser wavelength," 2020 EUVL Workshop (EUV Litho).

Presenting Author

Christian Gaida received his M.Sc. in 2013 and his Ph.D. in Physics from Friedrich Schiller University Jena in 2019. His research focuses on high-power fiber laser systems, particularly at 2 µm wavelength. He has made significant contributions to laser physics through a rigorous analysis of the wavelength dependence of nonlinear and laser-physical effects in thulium-doped fiber laser systems. His work has been recognized with the Applied Photonics Award and the Rohde & Schwarz Dissertation Award for the best doctoral thesis, titled "Power-Scaling of Ultrafast Thulium-Doped Fiber-Laser Systems."
Following his Ph.D., he joined Active Fiber Systems GmbH as a technical project manager and currently leads the research and development department.

P82

EUV and plasma sources using high energy solid state λ ≈ 2 μm laser drivers (Invited)

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

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

An efficient and compact diode-pumped, solid-state λ≈2μm Tm:YLF laser has been demonstrated that produces joule-class pulses in two distinct models: sub-picosecond pulses exceeding 1TW peak power using chirped pulse amplification [1] and >20J, nanosecond duration pulses [2]. We report on ongoing efforts to design and construct an upgraded Tm:YLF laser architecture that supports both pulse formats, while delivering energetic bursts of 1kHz pulse trains. This dedicated table-top laser system will be installed at the Jupiter Laser Facility at LLNL with the purpose of producing extreme ultraviolet (EUV) and hard x-rays sources using the laser in sub-picosecond and nanosecond modes, respectively. We will discuss the anticipated laser-target coupling efficiency at this novel high-energy, λ≈2μm interaction regime and the impacts to conversion efficiency into EUV and relativistic electron beams.
This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and funded by the Office of Science Microelectronics Science Research Center under Grant SCW1907

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

Presenting Author

Jackson Williams is a research physicist at Lawrence Livermore National Laboratory (LLNL) and the Program Lead for High-Intensity Laser-Driven Sources within the National Ignition Facility & Photon Science Directorate. Dr. Williams leads the development and execution of a scientific portfolio on particle and x-ray sources from intense lasers and for basic science and national security applications.

P83

Solid state laser drivers for EUV plasma sources (Invited)

Peter Moulton

MIT Lincoln Laboratory, 244 Wood Street, Lexington, MA USA

The present technology for EUV lithography, as implemented by ASML, involves a tin-based plasma source at 13.5 nm, driven by a high-average power CO_2 gas laser at 10.6 µm. The overall efficiency of the system is very low and the complex drive laser requires a large amount of space. We discuss the development of fiber lasers as a more efficient and compact alternative to the present gas laser system, and also as a driver for future plasma sources at shorter EUV wavelengths.

Presenting Author

Dr. Moulton is a member of the Senior Staff in the Laser Applications and Applications Group at the MIT Lincoln Laboratory. He received an A.B. in Physics from Harvard College in 1968 and M.S. and Ph.D. degrees in Electrical Engineering from MIT in 1972 and 1975 respectively.

Moulton's technical work began in the field of bulk solid state lasers, and in recent years has extended to include nonlinear optics and fiber lasers. At Lincoln Laboratory in 1982 he invented the Ti:sapphire laser, and he has also made important advances in high-power diode-pumped solid state lasers, parametric oscillators, and long-wavelength fiber lasers.

P84

Why High-Order Harmonic Generation Is the Optimal Source Solution for EUV Mask Review Systems (Invited)

Dong Gun Lee and Byung Gook Kim

ESOL (EUV Solution), Inc.
45, Dongtansandan 10-gil, Hwaseong-si, Gyeonggi-do, Republic of Korea

In actinic review systems for EUV masks, the use of both Laser Produced Plasma (LPP) sources, characterized as incoherent plasma light sources, and High Harmonic Generation (HHG) sources, which operate through a coherent EUV generation method, has been noted. This distinction in EUV source technology impacts the optical system design in review setups, which in turn determines product performance.

This presentation will address the industrial requirements and performance standards for EUV mask review systems. We will discuss our research on the optimal EUV source that best meets these demands and enhances system efficacy, highlighting the most suitable EUV source considering the industry's unique operational requirements

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.

P85

High-Harmonic Generation driven Extreme-Ultraviolet Scatterometry for Nanostructure Characterization (Invited)

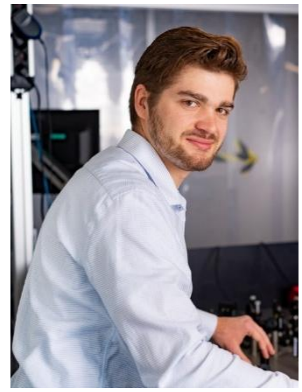
Francesco Corazza, Emmanouil Kachaoglou, Maximillian Lipp, Leo Guery, Zhonghui Nie, Lyuba Amitonova, and Peter M. Kraus

Advanced Research Center for Nanolithography and Vrije Universiteit Amsterdam, Science Park 106, 1098XG Amsterdam, Netherlands

We present a new approach based on a table-top HHG setup for the evaluation and extraction of the structural and material-related characteristics of nanostructures. Our focus is on grazing incidence scatterometry, a non-imaging metrology method for periodic nanostructures, operating in the extreme ultraviolet (XUV) spectral region (10−30 nm) in reflection geometry. By collecting and spectrally resolving only the 0th diffraction order, we can precisely reconstruct structural parameters of nanostructures with far below the illumination wavelength accuracy. We prove our measurements to be rapid due to an enhanced signal-to-noise ratio compared to higher diffraction orders, and resilient against distortions from non-uniform sample contamination. Experiments were performed on pairs of orthogonal gratings with the goal of retrieving morphological parameters such as linewidth and groove height. Morphological parameters are extracted solving the scatterometry inverse problem, which is framed as an optimization task. This task involves comparing the measured diffraction efficiencies to specialized libraries of simulated datasets computed via the Rigorous Coupled- Wave Analysis (RCWA) method.

Our initial experimental campaign has demonstrated groove height reconstruction accuracy below 2 nm and linewidth reconstruction accuracy of about 20 nm. A primary aim of this work is combining scatterometry with femtosecond time resolution, to probe of how the diffraction properties of a structured material change upon photoexcitation. For this reason, we have integrated an ultrafast time-resolved spectroscopy scheme within our scatterometer to investigate charge injection dynamics in complex heterostructures. Employing sub-10 femtosecond pulses allows access to charge transport phenomena within these layered structures. This provides means for new forms of functional metrology that can measure the quality of electric contacts in addition to structural parameters.

Presenting Author



Peter Kraus is the group leader of the “High-harmonic generation and EUV science” team at ARCNL, and associate professor of physics at the Vrije Universiteit Amsterdam. Since July 2024, Peter has also been part of the ARCNL management team as head of the metrology department. Peter’s research interests lie in developing extreme ultraviolet (EUV) and highly nonlinear light sources from gas and solid-state high-harmonic generation, and applying them for ultrafast spectroscopy and nanoscale metrology experiments with relevance to nanolithography.
Prior to joining ARCNL/VU in 2018 as group leader/assistant professor, Peter Kraus worked at the University of California, Berkeley (USA) on the development of new experimental techniques for investigating attosecond phenomena in solid-state materials. Peter obtained his PhD at ETH Zurich (Switzerland) in 2015. Here, he developed and advanced the techniques of high harmonic-spectroscopy for investigations of electronic and nuclear structure and dynamics of molecular systems.

P86

High repetition rate, high average power XUV sources based on High Harmonic Generation

B. Manschwetus[1], T. Braatz[1], S. Starosielec[1], S. Rajhans[2], E. Escoto[2], M. Sumfleth[3], D. Laumer[3], H. Goudarzi[1], C. M. Heyl[2,4,5], M. Wieland[3], M. J. Prandolini[1,3], T. Gorkhover[3], M. Drescher[3], M. Schulz[1], R. Riedel[1]

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[2]*Deutsches Elektronen Synchrotron (DESY), Hamburg, Germany*
[3]*Universität Hamburg, Institut für Experimentalphysik, Hamburg, Germany*
[4]*Helmholtz-Institut Jena, Jena, Germany*
[5]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*

High harmonic generation (HHG) sources produce coherent laser-like radiation in the Extreme-Ultraviolet (EUV/XUV) and soft X-ray spectral range with femto- or attosecond pulse durations. These sources are valuable tools in scientific and industrial applications, enabling high-resolution imaging of nanostructures in EUV lithography and ultrafast spectroscopy for studying solar cells, catalysis, and next-generation semiconductors. To meet these demands, HHG sources must offer high repetition rates, stability, and high average power.

Class 5 Photonics is developing the Moonlander HHG source using robust high-power femtosecond Ytterbium (Yb) lasers combined with multipass cell pulse post-compression technology. The current system, driven by the Class 5 Black Dwarf laser, has achieved XUV output powers of 1.4 μW for argon and 2.8 μW for krypton integrated over the 22-75 eV range, using 17 W average power at 100 kHz. Further power scaling is underway, with a recent setup using a 50 W laser at 750 kHz. The next phase involves demonstrating stable operation with driver lasers at 200 W and 500 W within the MEGA-EUV research project in collaboration with DESY, the University of Hamburg, and Amphos, aiming to advance HHG technology for industrial applications.

[1] X. F. Li et al., Phys. Rev. A 39, 5751–5761 (1989)
[2] A.Viotti et al., Optica 9, 197-216 (2022)

Presenting Author

Bastian Manschwetus, Head of Research and Development EUV/SXR sources, graduated 2010 at the Max-Born Institute Berlin investigating the behavior of atoms and molecules in strong laser fields in his PhD project. With a Marie-Curie fellowship he joined then the group of Pascal Salières at CEA Saclay (France), now diving into the field of attosecond physics by high harmonic generation and atomic and molecular spectroscopy. From 2013, Bastian moved to the Lund Laser Center to work with Nobel price laureate Anne L'Huillier and Per Johnsson on the development of a high peak power EUV source. In 2015, he became team leader for the pump probe laser operation at the Free-Electron Laser FLASH in Hamburg. In 2022 he joined Class 5 Photonics as project leader for developing industrial-grade EUV/soft-X-ray sources.

P87

Nanoscale Metrologies using Coherent EUV Sources (Invited)

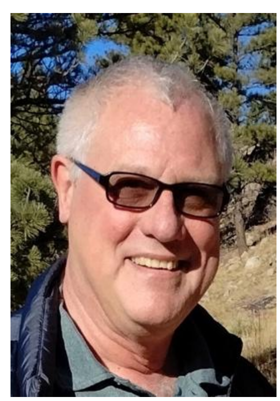
Henry C. Kapteyn

JILA, University of Colorado and NIST, and KMLabs Inc.

Tabletop-scale laser-based coherent EUV sources are demonstrating their potential for metrology applications in microelectronics and other industries. In my talk, I will discuss collaborative work in our group using EUV scatterometry and imaging for nondestructive evaluation of industry-relevant samples that demonstrate unique capabilities in this approach.[1-5] EUV scatterometry was used to characterize a periodic polymer-based optical metamaterial otherwise susceptible to SEM damage, as well as the dishing that occurs on planarization of copper contact arrays with sub-nm precision. EUV diffractometry measurements were shown to agree with CD-SAXS for characterizing metrology targets. Finally, full field coherent diffractive imaging was used to obtain spatial and depth resolved maps of the optical properties of nanostructures, with nm-resolution.

[1] M. Tanksalvala *et al.*, "Nondestructive, high-resolution, chemically specific 3D nanostructure characterization using phase-sensitive EUV imaging reflectometry," (in English), *Science Advances,* Article vol. 7, no. 5, p. 11, Jan 2021, Art no. eabd9667, doi: 10.1126/sciadv.abd9667.
[2] Y. Esashi *et al.*, "Tabletop extreme ultraviolet reflectometer for quantitative nanoscale reflectometry, scatterometry, and imaging," *Review of Scientific Instruments,* vol. 94, no. 12, p. 123705, 2023, doi: 10.1063/5.0175860.
[3] N. Jenkins *et al.*, "EUV scatterometry: low-dose characterization of polymer-based metamaterials," *SPIE Advanced Lithography + Patterning,* vol. 12955, 2024, doi: 10.1117/12.3009911.
[4] C. Klein *et al.*, *Optimized EUV Scatterometry Measurements with Tunable High Harmonic Generation and the Fisher Information Matrix* (SPIE Advanced Lithography & Patterning). San Jose, CA: SPIE, 2025.
[5] B. Barnes *et al.*, *Lab-based multi-wavelength EUV diffractometry for critical dimensions* (SPIE Advanced Lithography & Patterning). San Jose, CA: SPIE, 2025.

Presenting Author



Henry C. Kapteyn is Professor of Physics at the University of Colorado at Boulder, a Fellow of JILA, and the CTO of Kapteyn-Murnane Laboratories Inc. (KMLabs). He is well known for his work in using high harmonic generation to coherently upconvert light to make small-scale laser-like EUV sources. He has published several hundred papers in topics ranging from laser science and engineering to materials to nanoimaging. His awards include the OSA Adolph Lomb Medal and R.W. Wood Prize, the ACS Ahmed Zewail Award, the APS Arthur Schawlow Prize, and the Benjamin Franklin Medal in Physics.

P91

Cost-Effective EUV Light Sources for High-Volume Manufacturing (Invited)

Henry Chou

Energetiq Technology, Inc., Wilmington, MA 01887, USA

Extreme ultraviolet (EUV) lithography is increasingly being adopted in the next generation of high-density chip manufacturing. To support high-volume manufacturing, reliable inspection equipment must be made commercially available. EUV light sources are the powertrain of these inspection tools. Thus, the light sources require a high level of performance and stability while maintaining a low cost of ownership. Energetiq Technology has been offering high-performing EUV light sources for nearly 20 years and is at the forefront of integrating reliable light sources into commercially available equipment. Key applications include 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, mitigating the risk of defects that result in yield loss on printed wafers. Energetiq will discuss their technology, products, and roadmap to support EUV lithography for high-volume manufacturing.

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 from the University of Notre Dame and an EMBA from Baruch College, CUNY. Henry has worked for various capital equipment suppliers in the semiconductor, renewable energies, and consumer electronics industries.

P92

Applications of EUV Metrology Tools (Invited)

Matt Hettermann, Dave Houser, Chami Perera, Patrick Naulleau

EUV Tech Inc., Martinez CA, USA

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

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

P93

Numerical simulations for accelerating productivity and equipment design in semiconductor manufacturing

José Fonseca

FS Dynamics

Semiconductor manufacturing is a highly complex process that involves multiple stages, including photolithography, etching, deposition and cleaning — each requiring precision at the micro- and nanoscale. The interplay of complex physical and chemical interactions in these processes makes experimental optimization challenging, costly, and time-consuming. Numerical simulations provide a crucial advantage by offering predictive insights, enabling virtual prototyping, and optimizing process parameters before physical testing, ultimately reducing development time and costs.

FS Dynamics, with over 20 years of expertise in Computer-Aided Engineering (CAE), supports R&D teams in leveraging simulation to enhance productivity and optimize equipment design. This presentation will showcase our advanced modeling capabilities relevant to semiconductor manufacturing.

We will explore simulation-driven solutions for lithography, including reticle heating, contamination management, defectivity (particles), and flow induced vibration. Additionally, we will explore simulations for surface coating processes, plasma-based etching, multiscale fluid-molecular dynamics for feature profile evolution, and laser-produced plasmas for extreme ultraviolet (EUV) and broadband light sources. These case studies demonstrate how numerical simulations facilitate process optimization, enhance equipment performance, and drive innovation in semiconductor manufacturing.

Presenting Author

José Fonseca is Group Manager and CFD Specialist at FS Dynamics Germany GmbH. He received MSc. degree in Mechanical Engineering at the Federal University of Santa Catarina, Brazil. José brings vast experience of flow and thermal modelling applied to home appliances, HVAC and more than 13 years at semiconductor industry. Currently, José is leading a team of high skilled simulations engineers focusing on tackling the most challenging problems of the semiconductor industry by means of simulation.

P94

About X-ray metrology and the aftermath (Invited)

Victor Soltwisch

Physikalisch-Technische Bundesanstalt, Berlin, Germany

The development of modern X-ray metrology is much like raising children. Just when you think you have solved all the problems, new ones appear. You feel your way through a dark room, only to find that the room has changed again after two steps. This lecture is a lyrical tale of woe about the development of various EUV and X-ray measurement techniques. To be honest, it might seem simple to illuminate a sample at different angles and collect different signals based on the same physical principle: the interaction between light and matter. However, the trick is not to choose a nice name for the method such as GISAXS, XRR, CD-SAXS, GIXRF, GEXRF, EUV scatterometry, hybrid approaches or ellipsometry, but to develop a measurement approach that usually involves non-straightforward data analysis. Yes, of course measuring is an important profession. And metrology is the art of measurement, but the real work and challenge often begins afterwards. Countless PhD students at PTB have had to suffer when their supervisor arrives with a great new set of measurement data and happily says: “Look, isn't that cool? We can probably use that! Evaluate the data and do a few simulations. It's really easy”.

I'm going to tell you about the "it's really easy" in this talk. And, of course, I will also explain why it is so important that a national metrology institute measures material parameters and why this is extremely important for the optical metrology of semiconductor structures.

Presenting Author

Victor Soltwisch, has been working with synchrotron radiation for more than 25 years. Since 2019 he is leading the EUV nano-metrology group of the German national metrology institute (PTB) at the two electron storage rings BESSYII and Metrology Light Source located in Berlin-Germany.

During his PhD he worked from 2007 to 2010 at the Helmholtz-Zentrum Berlin at the undulator beamline UE46 in the field of resonant X-ray scattering on HTC cuprates and developed a new UHV diffractometer. In 2011, he also worked for a short time in industry at the small company BESTEC GmbH, which manufactures EUV reflectometers for Zeiss SMT. In 2012 he started his career at PTB as a postdoc in the former EUV radiometry working group. During this time, he specialized in particular in the numerical modeling of different EUV and X-ray measurement methods, which led to the formation of a new working group in 2019. The working group has currently grown to over 10 scientists and covers a wide variety of methods and is actively developing them further. From GISAXS, GIXRF, GEXRF in the soft X-ray range to EUV scatterometry and reflectometry and VUV ellipsometry and novel hybrid techniques to increase sensitivities. The measurement of optical fundamental parameters of materials has become a core business of the working group.

P95

Tools and solutions for actinic EUV metrology (Invited)

A. Biermanns-Föth, C. Pampfer, T. Missalla, C. Phiesel, R. Lebert

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At RI Research Instruments we design, manufacture, test and deliver systems and solutions based on existing building blocks and tailored to the needs of our customers. RI's EUV application experience is based on a broad source portfolio with stand-alone DPP and LPP sources for XUV together with an established supply chain in advanced EUV optics, detectors and spectral filtering. We have 20 years of experience in design, machining and assembly of ultra-clean components in ultra-high vacuum and cleanroom applications, including ultra-clean sample handling, loading and manipulation. Our research and application laboratories support such developments by enabling proof of concepts or tests of critical components with available EUV-sources, components and test installations.

Besides our work on EUV metrology, we have set standards for building particle accelerators around the world, from delivering normal-conducting as well as superconducting components up to turn-key accelerator systems. Our expertise is used in demanding applications that range from nuclear fusion and medical isotope production to the fabrication of components and systems for the semiconductor supply chain.

In this contribution, we highlight some of our EUV concepts, systems and capabilities.

Presenting Author

Andreas Biermanns-Föth is the Head of Business Section "Photon Instrumentation / EUV Systems" at RI Research Instruments. He received his PhD in Physics at the University of Siegen, working on the characterization of semiconductor nanostructures. In his scientific career, he has been developing synchrotron-based nano-focusing techniques and novel coherent diffraction methods. After joining RI Research Instruments as project manager in 2014, he has been focusing on developing custom tailored EUV metrology tools for the semiconductor supply chain.

P96

Studying the interaction of EUV and plasma with scanner construction materials (Invited)

Jacqueline van Veldhoven

TNO, Stieltjesweg 1, 2628CK, Delft, the Netherlands

In EUV lithography machines, not only the optical elements interact with the EUV light and EUV-induced plasma, but any construction materials used in the machine may also be exposed to plasma and to scattered light. Understanding how construction materials react to this kind of environment may be crucial for continued peak performance of the scanners.

At TNO, we employ a variety of techniques to understand the effects of scanner-like conditions on construction materials. At our EUV-beamline facility EBL2, we have the ability to expose samples to EUV under controlled conditions, allowing to study the effects of EUV-only, or of EUV combined with EUV-induced plasma. Combined with exposures in dedicated plasma setups, this enables a deeper understanding of the interplay of EUV and plasma effects.

Many EUV-material interactions are dominated by secondary electron generation. Since secondary electron generation also plays a large role when electrons impinge on a surface, exposure to an electron beam may generate similar effects in the material as exposure to EUV does. An additional advantage is that the usage of an egun expands the experimental parameters that are available. Therefore, this is one more technique we use to deepen our understanding of the behaviour of construction materials in EUV scanners.

Presenting Author

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

P101

Synthesis, Characterizations, and Ligand Substitution of a Non-Alkyl Tin Oxo Cluster as an Inorganic Resist for EUV Lithography

Hyeok Yun[1], Soyeong Heo[1], Jiyoung Bang[1], Minyeob Kim[1], Hyung-Bae Moon[2], Siwoo Noh[3], Geonhwa Kim[3], Hee-Seon Lee[4], Kyuyoung Heo[4], Sangsul Lee[3], Ki-Jeong Kim[3], Cheol-Min Kim[2], and Hyun-Dam Jeong[1]

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[2]*4Chem Laboratory, Suwon, 16229, Republic of Korea*
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We synthesized a novel non-alkyl tin-oxo cluster, CNU-TOC-01(4C-C), from $SnCl_2$, H_2O, and pyrazole, and evaluated its applicability in e-beam lithography (EBL) and extreme ultraviolet lithography (EUVL). Using field desorption time-of-flight mass spectrometry (FD-TOF MS) and small-angle X-ray scattering (SAXS), we proposed a cyclic molecular structure for CNU-TOC-01(4C-C) with the molecular formula $Sn_4Cl_3(C_3N_2H_4)(C_3N_2H_3)H_4O_8$. Three distinct peaks identified in the ^{119}Sn NMR spectrum support this proposed cluster structure, although complete structural elucidation is still underway. CNU-TOC-01(4C-C) exhibited a high EUV linear absorption coefficient of 20.7 μm^{-1}, achieving a line-edge roughness (LER) of 3.7 nm and a half-pitch (HP) resolution of 18 nm in EUV lithography. Furthermore, successful ligand substitution of CNU-TOC-01(4C-C) was confirmed by the detection of mixed substituted and unsubstituted ligand peaks via FD-TOF MS analysis. Specifically, substitution with acetic acid significantly improved the electron beam (5 keV) sensitivity to 19 $\mu C/cm^2$ and enhanced the EUV sensitivity, reducing the dose-to-size (DtS) from 105 mJ/cm^2 to 45 mJ/cm^2. Our ongoing research focuses on clarifying the structure of CNU-TOC-01(4C-C) and further enhancing its lithographic sensitivity through systematic ligand substitutions using various functional groups.

Presenting Author

Soyeong Heo received her B.S degree from the Department of Chemistry at Chonnam National University, and she is currently studying for a M.S in the Department of Chemistry at Chonnam National University. Her research focuses on the development of inorganic EUV photoresist.

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Improved Sensitivity of CNU-TOC-01(4C-C), a Tin-Oxo Cluster-Based EUV Inorganic Resist, via Position-Selective Purification

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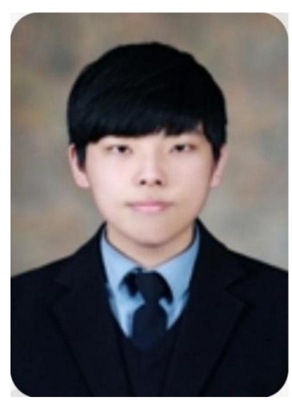
To achieve the high etch resistance and substantial EUV absorption coefficient, required for EUV resists, we synthesized CNU-TOC-01(4C-C), a tin oxo-cluster with an excellent photoionization cross-section. In EUV lithography, CNU-TOC-01(4C-C) demonstrated successful patterning of a 22 nm half-pitch line & space structure at an exposure energy of 105 mJ/cm^2, indicating its potential applicability as an EUV inorganic resist material. However, the initially synthesized CNU-TOC-01(4C-C) could not fully exhibit its intrinsic molecular properties due to residual impurities from incomplete purification. In this study, we employed position-selective purification to isolate pure CNU-TOC-01(4C-C) from these impurities, which were subsequently characterized by Sn, C, and H NMR spectroscopy. This analytical approach clarified how impurities affected the resist performance. After purification, the impurity-free CNU-TOC-01(4C-C) exhibited significantly enhanced electron-beam sensitivity (3.14 $\mu C/cm^2$) and improved contrast (4.8), along with increased EUV sensitivity. These results underscore the considerable promise of purified CNU-TOC-01(4C-C) as a next-generation inorganic resist for EUV lithography.

Presenting Author

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



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Development of a Monomeric Inorganic Resist (CNU-TIDO-AA) for EUV Lithography

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Extreme ultraviolet lithography (EUVL) is an essential technology for the miniaturization of semiconductor devices. However, the continuous demand for higher resolution and line-edge roughness control in patterning has pushed the development of alternative resist materials. Inorganic resists have attracted significant attention due to their superior mechanical strength and etching resistance, making them promising candidates for EUVL applications. In this study, we synthesized CNU-TIDO-AA, and investigated its potential as an EUV resist material. The molecular structure of CNU-TIDO-AA was elucidated using MALDI-TOF mass spectrometry, X-ray photoelectron spectroscopy (XPS), and Fourier-transform infrared spectroscopy (FT-IR). The monomer-derived thin films demonstrated a unique chemical contrast mechanism under EUV exposure, which enables high pattern fidelity without relying on traditional acid-catalyzed or condensation pathways. To validate its lithographic performance, we systematically evaluated the sensitivity (D_{50}) and contrast of CNU-TIDO-AA under both electron beam (E-beam) and EUV exposure. Furthermore, chemical contrast behavior of the CNU-TIDO-AA film was investigated before and after exposure to E-beam and EUV radiation, using FT-IR, XPS, TOF-SIMS, and spectroscopic ellipsometry (SE). These findings highlight CNU-TIDO-AA as a promising candidate for next-generation EUV resists, offering a new approach to high-resolution nanopatterning.

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.

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Synthesis and Evaluation of Function-Integrated Inorganic Molecular Resists for EUV Lithography

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2,4,6,8-tetrahydroxy-2,4,6,8-tetramethyl-cyclotetrasiloxane (TS-T4(OH)) exhibits superior dry etch resistance and structural rigidity. In particular, the formation of dense intermolecular hydrogen-bonded networks via OH groups is believed to effectively suppress secondary electron diffusion. However, the inherently low EUV absorption coefficient of silicon (Si) remains a significant challenge for achieving sub-nanometer-scale patterning. In this study, we designed and synthesized molecular resists with a core-arm structure using tetrasiloxane-tetraoxy (TS-T4(O)) as the inorganic core, integrating electron-generating (α), photoacid-generating (β), and acid/electron-labile (δ) groups as functional arm structures. Initially, we synthesized a simplified molecule containing only the photoacid-generating (β) unit and blended it with polymethylmethacrylate (PMMA) to evaluate its acid-generation efficiency by measuring electron beam sensitivity. The electron-generating structure (α) was incorporated with tin (Sn), chosen for its high EUV absorption coefficient, while the labile group (δ) was designed to dissociate upon interaction with electrons generated from structure (α) and protons produced by structure (β). Two types of function-integrated molecular resists were synthesized: one integrating electron-generating, photoacid-generating, and labile groups (α+β+δ), and the other combining electron-generating and labile groups (α+δ). Electron beam lithography (EBL) confirmed their negative-tone behavior and evaluated their sensitivity. Subsequently, EUV lithography tests based on the EBL results demonstrated the resists' potential for fine-pattern lithography.

Presenting Author

Gahyun Lee received her B.S degree from the Department of Chemistry at Chonnam National University, and she is currently studying for a M.S in the Department of Chemistry at Chonnam National University. Her research focuses on the development of inorganic EUV photoresist.

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Numerical simulations application in semiconductor manufacturing

Alessandro Ruocco

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FS Dynamics stands for 'Fluid Structural Dynamics', we are a company focused on Computer Aided Engineering (CAE) consultancy, a discipline that combines fundamental physics, mathematics, and high-powered computing. Besides technical skills, we help clients to easily translate models into tangible product improvements.

Our expertise falls in the following categories:

- **Computational fluid dynamics**: our areas of competence include microfluidics, heat and mass transfer, turbulence, multiphase, and much more;
- **Finite element analysis**: especially in acoustics, transient thermal and mechanical analysis, fatigue, structural-induced noise, fluid structure interaction (FSI) and structural analysis of polymers and composites.
- **Plasma modelling**: we can assist in laser-produced and discharge-produced plasmas for EUV and broadband sources, and plasma processing for etching and atomic layer deposition;
- **Surface chemistry**: our expertise focuses mainly on molecular dynamics, where we model sputtering and ions depositions.

In this poster, we present examples of our modelling capability relevant to the semiconductor industry, spanning from microfluidics applied to lithography machine and surface coating, plasma processing simulations for etching, multiscale fluid-molecular dynamics model of feature profile, and laser-produced plasmas for EUV and broadband sources.

Presenting Author

Alessandro Ruocco is a Plasma Simulation Specialist at FS Dynamics. He received Bs and Ms degree in Physics at the University of Naples Federico II, Italy, and a PhD on plasma modelling for laser fusion from Celia laboratory, University of Bordeaux, France. Before joining FS Dynamics, he worked as a postdoc at Rutherford Appleton Laboratory, Oxford, UK.

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Platform to study effects of EUV-induced plasmas

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The talk will focus on the implementation of our proven FS5440 high power EUV source into a fully integrated, irradiation and analysis setup that allows for studying the effects of EUV irradiation and plasma generation on optical surfaces.
The FS5440 Source can provide 40 W/2πsr inband EUV radiation in arbitrary duty-cycles to reduce operational cost and to avoid the need for an optical shutter. Integrated into a source collector module with debris-mitigation and vacuum separation, an EUV irradiance >40 W/cm² on a spot diameter >1.8 mm with opening angle <5° can be achieved, to mimic the behavior of EUV lithographic tools.
To simulate the plasma atmosphere in such EUV tools, hydrogen with impurities can be finely dosed into the exposure chamber. Achieving the necessary accuracy in dosing of impurities requires a very clean atmosphere to begin with. Such, clean vacuum, low transmission of source/debris-mitigation working gases and high purity hydrogen are required. For this, the setup has an integrated hydrogen safety system, including hydrogen generation, purification and neutralization.
Having the know-how on EUV sources and their implementation into optical system at hand, Fraunhofer ILT has been developing a multitude of applications in collaboration with RWTH Aachen University, e.g., EUV laboratory-scale lithography for patterning and resist testing or EUV reflectometry for surface sensitive analysis.

Presenting Author

Jochen Vieker received his Master in physics in 2011 from Bielefeld University, for his work on high harmonic generation. Since then, he has been scientist in the EUV technology group at the Fraunhofer Institute for Laser Technology ILT and finished his *PhD* in physics in 2019 at RWTH Aachen University for his research on power and lifetime scaling of discharge based EUV sources. As senior engineer and project leader he contributes to the fields of EUV technology and laser-driven secondary sources and applications of ionizing radiation.

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Laser Diagnostics for EUVL Sources at Princeton Plasma Physics Laboratory

Alec Griffith

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Laser-produced tin plasmas serve as the source for state-of-the-art extreme ultraviolet lithography (EUVL). The thermodynamic properties of the plasma—its temperature, density, and their spatial and temporal profiles—greatly affect the conversion of infrared laser photons into EUV photons centered at a 13.5 nm wavelength. At the Princeton Plasma Physics Laboratory, we are developing a laboratory facility, SparkLight, to take advantage of plasma physics understanding to improve laser plasma EUV sources. We have constructed a tin rod target driven by an Nd:YAG laser paired with diagnostics including interferometry, Thomson scattering, and spectroscopy to characterize the plasma. Complementing this experimental work, we perform radiation hydrodynamic and particle-in-cell simulations for validation and parameter optimization. We will present results that integrate modeling and experimental data to characterize and optimize the EUV source.

Presenting Author

Alec Griffith is a postdoc at the Princeton Plasma Physics Laboratory, studying plasma processes in LPP EUV sources. He earned his PhD in Astrophysical Sciences from Princeton in 2024, specializing in the theory and modeling of high-intensity laser applications for short-wavelength sources and QED plasma diagnostics.

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The development of EUV and soft X-ray optical evaluation systems in TOYAMA

Akira Miyake

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

(1) Two-beam interference fine pattern exposure system
Interference exposure experiments using highly coherent synchrotron radiation light sources have been implemented to evaluate the resolution of resists. We discuss the possibility of implementing this exposure method using a compact plasma light source with low brightness and low coherence.
(2) EUV reflectometer
We are developing a stand-alone EUV reflectometer system that can evaluate the spectral reflectance of EUV multilayer mirrors with high accuracy. The reflectometer is equipped with a correction system so that it is not affected by fluctuation in the intensity and spectrum of the plasma light source.
(3) EUV transmitting component evaluation system
We are designing a system for evaluating the transmittance and scattering intensity distribution of EUV transmission optical components, as well as an optical system for durability evaluation using high-intensity beam irradiation

Presenting Author

Akira Miyake is a chief engineer at TOYAMA Co., Ltd. and is in charge of the optical design of X-ray optical systems. After studying X-ray astronomy at Osaka University, he joined Canon Inc. in 1987 and participated in the optical systems development of the X-ray and EUV exposure equipment. From 2015 to 2020, he also participated in the development of large astronomical telescopes and satellite optical systems.

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EUV Metrology at NIST

Stephanie L. Moffitt

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Metrology has been a key part of the development and growth of extreme-ultraviolet lithography (EUVL). NIST has a long history of supporting the expansion of EUVL metrology using the Synchrotron Ultraviolet Radiation Facility (SURF III). Our established capabilities include the characterization of EUV optics (performance and durability) and the calibration of EUV detectors. As EUVL has become increasingly important, research at NIST is evolving to develop new measurement services and metrology techniques. Ongoing research seeks to improve the metrology of EUV sources, including EUV radiometer and detector development and scintillator quantification. NIST is currently developing two new beamline facilities to expand our measurement services. The first will support optics reflectivity measurements of large and complex optics. The second will be a dedicated detector calibration facility, capable of providing measurements over a large wavelength range.

Presenting Author

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

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Engineered Hybrid Metal-Organic Clusters Resist for Next-Generation High-NA EUV Lithography

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The evolution of advanced semiconductor manufacturing has positioned extreme ultraviolet (EUV) as the cutting-edge patterning technology, especially with the emergence of high-numerical aperture (high-NA) systems. It imposed stringent requirements on next-generation (NG) resists, particularly in resolving the high-resolution half-pitch patterns, line-edge roughness, and sensitivity (RLS) trade-off. Hence, there is an urgent need for NG resist technology that seamlessly integrates high-resolution, line-edge roughness, and sensitivity (RLS) in the demanding regime of sub-20 nm patterning. Hybrid metal-organic clusters (MOCs), antimony (Sb) or analogue variants, have garnered attention as NG EUV resists due to their high absorption cross-section at EUV (λ~13.5 nm) and integrable molecular architecture. In this work, we unveil the innovative design, synthesis, and characterization of Sb or analogue MOCs functionalized with cross-linkable organic ligands, optimized for electron beam lithography (EBL), Helium Ion beam (HIBL), prelude to EUV patterning performance with tuneable chemical and structural resist formulations. These MOCs, composed of atomically precise inorganic cores coordinated with functionalized organic ligands, reveal that solubility switching upon exposure is governed primarily by ligand cross-linking, facilitates efficient sensitivity and high-resolution pattern formation with minimized roughness and tuneable development contrast due to irradiation transformations. It underscores their potential as resist platforms for enabling sub-20 nm half-pitch patterning in high-NA EUV lithography and will be instrumental in advancing the future of semiconductor technology.

Presenting Author

Prof. Satinder Kumar Sharma, Ph.D. (SMIEEE, IETE Fellow, SPIE Member), is a full professor in the School of Computing and Electrical Engineering at IIT Mandi. He earned his Ph.D. in Electronic Science from Kurukshetra University in 2007 and completed a postdoctoral fellowship at IIT Kanpur (2007-2010). He later joined IIIT-Allahabad in 2011 before moving to IIT Mandi in 2012, where he became a full professor in 2021. Prof. Sharma has raised over INR 4000 Lakhs for research from agencies like MeitY, DST, ISRO, and international bodies like DAAD and Semiconductor Research Corporation. He has collaborated with institutions such as IITs, Lawrence Berkeley National Laboratory (USA), and Stuttgart University (Germany). His research interests span microelectronics, CMOS devices, MEMS/NEMS, advanced lithography, sensors, photovoltaics, and self-assembly.

EUV

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