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Workshop Abstracts

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Contents

Abstracts

(Listed by Paper number)

P1

Lithographic Performance of The First Entirely Dry Process for EUV Lithography

Mohammed Alvi[1], Dictus Dries[1], Richard Gottscho[1], Kevin Gu[1], Benjamin Kam[1], Siva Kanakasabapathy[1], Da Li[1], Jeffrey Marks[1], Katie Nardi[1], Thad Nicholson[1], Yang Pan[1], Daniel Peters[1], Al Schoepp[1], Nader Shamma[1], Easwar Srinivasan[1], Samantha Tan[1], Clint Thomas[1], Boris Volosskiy[1], **Tim Weidman**[1*], Rich Wise[1], William Wu[1], Jun Xue[1], Jengyi Yu[1], Christophe Fouqu[2], Rolf Custers[2], Jara Garcia Santaclara[2], Michael Kubis[2], Gijsbert Rispens[2], Lidia van Lent-Protasova[2], Mircea Dusa[3], Patrick Jaenen[3], and Abhinav Pathak[3]

[1]LAM Reserach

[2]ASML

[3]IMEC

The lithographic performance of a new entirely dry EUV photoresist platform will be described. Photoresist films are applied using reactive organometallic precursors in a vapor phase process that provides uniform, homogeneous films stable to air and visible light. EUV exposure and subsequent bake steps induce crosslinking and densification, while unexposed areas remain hydrophobic and freely soluble in common organic solvents. This has facilitated the extensive characterization of lithographic patterning performance using NXE-3400 tools at both IMEC and ASML – initially employing conventional (solvent based) negative tone development (NTD).

In contrast to typical spin-on processes, dry deposited film thickness appears insensitive to substrate surface chemistry, making applied film thickness easily controlled/proportional to deposition time. EUV dose requirement (dose to size, or DtS) to print 16nm HP lines (in 32nm P dense l/s patterns) was ~45 mJ/cm^2 showing surprisingly little sensitivity to film thickness between 10nm and 25nm. A baseline (20nm thick) resist film patterned on the NXE-3400 resolves 13 nm HP L/S at a dose of 48 mJ/cm^2 and LWR of 2.7nm, translating to a Z-factor of 0.77, results roughly on par with those reported for leading edge spin-on metal oxide formulations. Full wafer CD uniformity of the baseline process measured at 16nm HP gave a 3σ of 2.4%, with an in-lot stability/variability of less than 1 mJ/cm^2 3σ DtS.

Significantly improved performance, particularly apparent at 13nm HP, is enabled using a new dry etch process -selective for unexposed films for pattern development. Key benefits can be attributed to the avoidance of capillary forces associated with solvent evaporation from between fine features. Full wafer FEM comparisons (over a large dose range) of identical dry deposited resist films (developed using wet vs. new dry etch technology) demonstrate an enormous increase in pattern collapse free process window. For example, dense underexposed features exhibiting CD values well below target (i.e. 10 nm vs. 13 nm)

remain standing and intact using dry development but are absent due to delamination or collapse at identically exposed die/patterns following solvent development. Additional benefits include reduced LWR and Z factor, together with cost and environmental advantages linked with eliminating liquid developers.
By combining vapor phase deposition and dry etch development, this new resist platform provides the first entirely dry (organic solvent and developer free) lithographic process applicable to high volume EUV manufacturing. Finally, extendibility down to 9nm HP was been demonstrated by exposures performed on the 0.5 NA micro-field exposure tool (MET5) at Lawrence Berkeley National Laboratory.

Presenting Author

Tim Weidman received his Ph.D. (focusing on Organometallic Photochemistry) from U.C. Berkeley in 1986. He spent the following 11 years at AT&T Bell Laboratories developing both “wet” and dry (plasma) based approaches to new organosilicon materials, and performed an early demonstration of dry DUV lithography based on the photo-oxidative patterning of plasma polymerized organosilicon hydrides. Moving back west – first to Applied Materials and later Sunpower, he spent the next 20 years leading a wide variety of programs applying new chemistry and hardware to leading edge semiconductor device or high efficiency solar cell fabrication. In 2017 he moved to Lam Research, where as Senior Technical Director he is focused on developing high performance process technology for all dry EUV lithography.

P2

EUV Lithography and The Materials That Propel It Forward

Emily Gallagher, Eric Hendrickx, Ryoung han Kim, Philippe Leray, Vicky Philipsen, Ivan Pollentier Danilo DeSimone, Paulina Rincon, Kurt Ronse, Marina Timmermans

IMEC
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Use of EUV lithography in manufacturing should not be confused with EUV lithography development completed. Imec's industry roadmaps clearly show EUV inserted for N7 and beyond using both single and double patterning strategies. This achievement of patterning strategies and resolution is important, but that achievement relies on fundamental development in materials. In this keynote, the EUV roadmaps will be introduced and patterning accomplishments described. Then more time will be devoted to the role of materials in enabling EUV lithography. More specifically, EUV resists, mask absorbers and EUV pellicle membranes will be used to demonstrate how fundamental material studies are needed to propel the semiconductor industry roadmap forward. EUV photoresist materials not only enable resolution, but also are key to controlling stochastic defects. Mask absorbers can be modified to enhance NILS and minimize mask 3D effects. Finally, yield is a critical component to any semiconductor wafer manufacturing solution and a high-transmission, EUV pellicle is essential to preserving high yield on the EUV processes that the industry worked so hard to develop. Foundational material selection and recent updates on the EUV pellicle will be included.

Presenting Author

Emily Gallagher is a Principal Member of Technical Staff at imec, focusing on pellicle membrane development, EUV imaging and photomasks. Emily received her PhD in physics studying free electron lasers at Dartmouth School of Graduate and Advanced Studies before shifting to the semiconductor industry and IBM where her work ranged from electrical wafer characterization to lithography. She led the EUV mask development work for IBM before joining imec in 2014. She has collaborated on ~100 technical papers, holds ~30 patents and is an SPIE Fellow.

P3

EUV Lithography and Its Enablement of Future Generations of Semiconductor Devices

Nak Seong

ASML

EUV lithography has started to be used for high-volume manufacturing (HVM) of the 7-nm and 5nm logic nodes and its key benefits were reported such as enabling faster time to market and better interconnect performance compared to multiple patterning solutions by chip manufactures [1,2]. In this presentation, we give an update on lithographic performance results obtained from our latest NXE:3400 systems and discuss opportunities of EUV lithography to enable future logic and DRAM nodes to deliver better chip performance and cost. Optimized solutions for the layouts and patterning requirements of given device and layer are proposed to enable low k1 imaging for EUV lithography.

[1] E Jung, 1.1.1., IEDM 2018
[2] G. Yeap, 36.7.1, IEDM 2019

Presenting Author

Nak Seong is the Director of Technology Development Center (TDC) of US/Asia of ASML. He joined ASML TDC in November 2013. His work covers studies of future semiconductor technology trends to understand requirements of future patterning technologies. From 2007 to 2013, he worked at Cymer guiding product developments and driving customer interactions by analyzing patterning impact of light sources. From 2001 to 2006, he worked at IBM where he worked on high NA imaging, 157 lithography development, and DFM for low k1 imaging. He started his career at Samsung in Korea in 1989 where he developed lithography processes for DRAM in early days, developed RET for low k1 imaging solutions for memory products and scanner evaluation methods to support them. Nak graduated from Kyung-Hee University in 1989 with BS in Physics.

P4

Deep Learning for Science

Prabhat

Lawrence Berkeley National Lab (LBL)

Deep Learning (DL) has revolutionized the fields of Computer Vision, Speech Recognition and Robotics. DL has made recent inroads in solving a range of data analytics problems in Astronomy, Cosmology, Climate, High-Energy Physics, Neuroscience and BioImaging. Researchers are actively exploring applications of DL to enhancement, augmentation and replacement of conventional simulation codes. This talk will review recent progress in both classes of DL applications at NERSC, and comment on system-level requirements for DL at scale. The talk will conclude with a speculation on potential applications of DL to EDA.

Presenting Author

Prabhat leads the Data and Analytics Services team at NERSC; his group is responsible for supporting over 7000 scientific users on NERSC's HPC systems. His current research interests include Deep Learning, Machine Learning, Applied Statistics and High-Performance Computing. In the past, Prabhat has worked on topics in scientific data management; he co-edited a book on 'High Performance Parallel I/O'.

Prabhat is the Director of the Big Data Center collaboration between NERSC, Intel, Cray, UC Berkeley, UC Davis, NYU, UBC, Oxford and Liverpool. The BDC project aims at enabling capability, data-intensive science applications on the NERSC Cori system. Prabhat received a B.Tech in Computer Science and Engineering from IIT-Delhi (1999); ScM in Computer Science from Brown University (2001) and a PhD in Earth and Planetary Sciences from U.C. Berkeley (2020).

Prabhat has co-authored over 150 papers spanning several domain sciences and topics in computer science. He has won 5 Best Paper Awards, 3 Industry Innovation Awards, and he was a part of the team that won the 2018 Gordon Bell Prize for their work on 'Exascale Deep Learning'.

P5

EUV Lithography: 0.33NA in HVM and Preparation for Future Nodes

Steve Carson

Intel Corporation

Extreme Ultraviolet lithography enters volume production as many of the success criteria for the technology are being met. EUV brings enhanced resolution capability with respect to 193nm-immersion, driving it as a replacement for the current incumbent technology. For EUV to be a successful replacement in high volume manufacturing, EUV technology demonstrations have to be exceeded, and remaining challenges need to be addressed. At the same time, increasingly aggressive targets for future technology nodes are creating new challenges for EUV as a manufacturing technology. In this presentation, the current status of EUV towards high volume manufacturing will be reviewed and near-term and long-term challenges for future EUV technologies will be discussed.

Presenting Author

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

P11

Current Progress in a-PSM Mask Development (Tentative Title)

Vibhu Jindal

AMAT

Presenting Author

P12

Actinic Tools using Coherent EUV Source for High Volume Manufacturing (Invited)

Dong Gun Lee

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

The coherent Extreme Ultra-Violet (EUV) source provides a compelling alternative to incoherent sources in EUV mask metrology, alleviating the engineering level of EUV optics and consequently reducing system cost of ownership. Significant progress has been made in the development of ESOL's actinic tools by providing a coherent EUV source that meets the requirements in the diffractive optical system [1-2]. This presentation introduces the application of coherent EUV sources for current High-Volume Manufacturing (HVM) in EUV lithography and its application to the next high-NA EUV lithography.

References

[1] **D. G. Lee**, J. –H. Kim, K. H. Hong, and C. H. Nam, "Coherent control of high-order harmonics with chirped femtosecond laser pulses," Phys. Rev. Lett. **87**, 243902 (2001).
[2] **D. G. Lee**, J. J. Park, J. H. Sung, and C. H. Nam, "Wave-front phase measurements of high-order harmonic beams using the point-diffraction interferometry," Opt. Lett. **28**, 480 (2003).

Presenting Author

Dong Gun Lee is the Chief Technology Officer of ESOL. He received an M.S. and Ph.D. degree in Physics from the Korea Advanced Institute of Science and Technology (KAIST). Prior to joining ESOL, he developed tools for EUV mask production for the past 16 years as a Senior Principle Engineer at the Samsung Electronics Semiconductor Research Institute.

P13

Pathfinding the Novel Absorber Materials for High-NA EUV lithography (Invited)

Jinho Ahn

Hanyang University
EUV-IUCC (Industry University Collaboration Center)

Over the past few years, extreme ultraviolet lithography (EUVL) has been matured to meet the requirements required for high volume manufacturing (HVM) with a numerical aperture (NA) of 0.33. To enable cost-effective shrinkage beyond the 3 nm technology node, a higher NA (0.55) EUV platform with anamorphic optics is being developed. However, the performance of conventional Ta-based mask is limited due to low contrast and severe mask 3D effect in high NA system. As a result, advanced absorbers which can replace the conventional Ta-based mask are required. In this paper, the imaging performance of novel absorbers such as high extinction coefficient (high-k) absorber and attenuated phase shifting absorber will be presented. And also, the mask fabrication issues such as dry etching and wet cleaning will be discussed.

Presenting Author

Jinho Ahn received his B.S. and M.S. degrees from Seoul National University, and his Ph.D. degree from the University of Texas at Austin all in materials science and engineering. He worked for Microelectronics Research Laboratory at NEC, Tsukuba, Japan and joined Hanyang University in 1995 as a Professor of Materials Science and Engineering. He has been a leader of several national projects on advanced lithography. He has authored more than 200 technical papers and invented more than 45 patents. He is currently a member of the National Academy of Engineering of Korea and a board member of the National Nano Infrastructure Association. He also works as the director of EUV-IUCC (Industry University Collaboration Center).

P14

Multi-stack Ni Absorber EUV Mask for High Numerical Aperture Extreme-ultraviolet Lithography

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[3] EUV-IUCC (Industry University Collaboration Center)
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Extreme ultraviolet lithography (EUVL) began to be applied for high volume manufacturing (HVM) of 7 nm logic node. High NA EUV platform with anamorphic optics system (4X/8Y) is now being developed in order to extend resolution limit beyond the 3 nm technology node. Since conventional Ta-based EUV mask is expected to show severe mask 3D effect at sub 5nm node, a novel advanced EUV mask is highly required. In this study, we propose a novel concept of multi-stack EUV mask using Ni-based high extinction coefficient (k) absorber which can be used in sub 5 nm node. The high-k mask stack consists of absorber layers (Ni) and spacer layers (CrN). Since Ni shows high extinction coefficient compared to conventional Ta-based material, the imaging properties such as normalized image log slope (NILS) and aerial image contrast can be improved. Furthermore, our thinner structure of EUV mask mitigates the mask 3D effects such as non-telecentricity (nTC) and best focus shift. Also, it shows improved etchability and cleaning durability due to suppressed crystallinity of Ni by inserting CrN spacer layers. We expect this multi-stack EUV mask with Ni absorber layers and CrN spacer layers can be a solution for high NA system.

Presenting Author

Yoon Jong Han is a graduate student under Prof. Jinho Ahn in Hanyang University.

P15

EUV Pellicle Defect Review using EUV Ptychography Microscope

Byungmin Yoo[1,3], Dong Gon Woo[3], Young Woong Kim[2,3], Young Ju Jang[1,3], Seong Ju Wi[2,3] and Jinho Ahn[1,2,3]

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EUV pellicle which is an essential solution for EUV mask protection is being researched for high volume manufacturing (HVM). The pellicle inspection should be preceded before applying into the lithography process due to the possibility of wafer pattern loss caused by particles larger than a critical size.

In this study, the EUV pellicle defect review was performed by EUV ptychography microscope. It is based on high-order harmonic generation (HHG) EUV light source and ptychographic imaging algorithm which is based on multi-shot coherent diffractive imaging (CDI) method. We reconstructed the through-pellicle mask image from the captured diffraction patterns which have at least 60% redundancy between shots by using phase retrieval algorithm.

We evaluated defect detecting performance of EUV ptychography microscope by mapping the programmed defects on the pellicle and carried out through-pellicle mask imaging to confirm the impact of particle size on the final wafer pattern. In conclusion, we confirmed the feasibility of EUV ptychography microscope for EUV pellicle qualification and defect review.

Presenting Author

Byungmin Yoo is a graduate student under Prof. Jinho Ahn in Hanyang University.

P16

Reflectance Measurement of EUV Mask under OoB-Irradiation, and Hydrogen and Water Vapor Environments under the High Power EUV Irradiation (Invited)

Takeo Watanabe

University of Hyogo

As described on the IRDS roadmap, logic foundry producers have used EUV lithographic technology to adapted in HVM from 2019. However, many technical issues are still remained. The LPP source radiates not only EUV light but alsoout of band (OoB). The light contrast of the resist-pattern image on a wafer will be decreased by the OoB, which will increase the resist line-width-roughness (LWR) and decrease the resist-process window. As the reflectometer which can measure the reflectivity at 50 – 150 nm wavelength of VUV region does not exist, it is developed that an EUV and OoB reflectometer to evaluate optical properties and resist sensitivity at the beamline BL-3 in NewSUBARU synchrotron light facility. And it is measured that the reflectance of the component materials of EUV mask. It is found that the OoB reflectances of Mo/Si MLs and TaN absorber have approximately 30%. And those of TaN absorber.

As the hydrocarbon gas which is remained in a vacuum is formed a carbon contamination on a mirror and causes a reflectance drop in EUV lithography, the hydrogen gas is introduced in the EUV exposure tool to reduce the optics carbon contamination. Thus, to analyze the hydrogen and water effects of the Mo/Si MLs, the EUV irradiation tool in hydrogen and water vapor atmosphere is developed and installed at the BL09 long-undulator beamline of the NewSUBARU synchrotron light facility. The EUV power (light intensity) is 5.7 W/cm^2, and H_2 pressure is up to 5 Pa. The contamination removal and hydrogen damage are discussed.

Presenting Author

Takeo Watanabe received his Ph.D. from Osaka City University in 1990. He is Full Professor, Director of Center for EUV, and Dean Laboratory of Advanced Science and Technology for Industry, University of Hyogo. He is an expert of the EUV lithographic technology, including optics, exposure tool, mask and resist related technologies. He has authored over 200 technical papers, and he is international affair, and the organizing and program committee members, of the International Conference of Photopolymer Science and Technology (ICPST). He is also Conference Chair of the International Conference of Photomask Japan. And he is a program committee member of the International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN).

P17

Compact Modeling to Predict and Correct Stochastic Hotspots in EUVL (Invited)

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The goal of any lithographic process is to transfer the pattern on the reticle into a photoresist film with good fidelity. The quality of the resulting pattern is dependent on the uniformity of photon absorption events in a photoresist pattern from exposure and the subsequent photo-chemical reactions. Photon statistics become increasingly important as the brightness of the source decreases because the number of photon absorption events is the first in a chain of stochastic processes in photoresist pattern formation. In past technology nodes, using a bright excimer laser source, the effects of photon shot noise could be largely ignored. Extra attention could be paid to select patterns which are prone to stochastic failure during mask correction, optimization, and verification.

Extreme ultraviolet lithography (EUVL) systems though struggle from both low source brightness and low source throughput through the tool. For these reasons, photon shot noise will play a much larger role in image process development for EUVL than in DUV processes. Furthermore, the lower photon count increases the stochastic variation of all the processes which occur after photon absorption. This causes the printed edge to move away from the mean edge with increased probability. Thus, in any array of dense contacts there is some probability that a single contact will be missing or that two adjacent contacts will be merged. Similarly, there is some probability in a grating structure that a line may break, or a space may bridge. More importantly for lithography of complex wafer shapes in random logic or memory circuits, there is increased probability that select 2D patterns will fail due to stochastic variation. Therefore, it is essential to EUVL process development that stochastic edge position variation can be predicted at full chip scale.

This paper will present several strategies for stochastic-aware process development. More specifically, a compact model form and calibration flow for including stochastic probability bands in compact models suitable for full chip simulation will be presented. This model form can be calibrated either directly to experimental roughness data, or to statistical data from a rigorous EUV stochastic lithography model in-turn calibrated to wafer experimental data. The data generation, data preparation, and model calibration flows for the compact stochastic probability bands will be presented. We will show that this model form can predict patterns which are prone to stochastic pattern failure in realistic mask designs, as well as how this model form can be used downstream for full chip correction (e.g., SMO, OPC and/or ILT).

Presenting Author

Zac received his B.S, M.E, degrees in Microelectronic Engineering and his Ph.D. in Microsystems Engineering from the Rochester Institute of Technology where he studied under Dr. Bruce Smith. He has worked at Micron Technologies, TrueSense Imaging, and is currently employed as an Senior Applications Engineer at Synopsys, Inc. He is author or co-author of 28 papers, including peer-reviewed articles and conference proceedings. His main research interests are EUV optics and stochastic variation in lithographic processes.

P18

Effect of Annealing on Interfacial Quality of Ion Beam Sputtered Mo/Si Multilayers for EUV Mask Blanks (Invited)

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As Extreme Ultra Violet lithography (EUVL) becomes adopted into manufacturing, there is a continuous need to understand and improve the EUV-mask Mo/Si multilayer (ML) properties that impact reflectivity, as a function of both incidence angle and wavelength around the Central Wavelength (CWL). Key properties are the Mo and Si crystalline nature, and the roughness and depth of inter-diffusion at the Mo-Si interfaces. Over the course of mask manufacturing and usage, as it is exposed to further processing or EUV, the ML is exposed to thermal cycling, so stability is key. In this work we look at the impact of temperature annealing on the multilayer structure and interfaces. A nine (9) bilayer Mo/Si ML stack, consisting of three different Mo/Si thicknesses, was deposited using Veeco LDD-IBD equipment (low-defect density ion beam deposition) as depicted in Figure 1. The samples were then annealed at temperatures between 60°C and 300°C. The thermally-treated interfaces were probed using HR-TEM for thickness and crystalline nature of the inter-diffusion layer, while the chemical nature was probed using EELS. We also analyzed thermally treated single bilayer structures by x-ray reflectivity. Finally, we simulated the impact of the interfacial observations, using McLeod simulations.

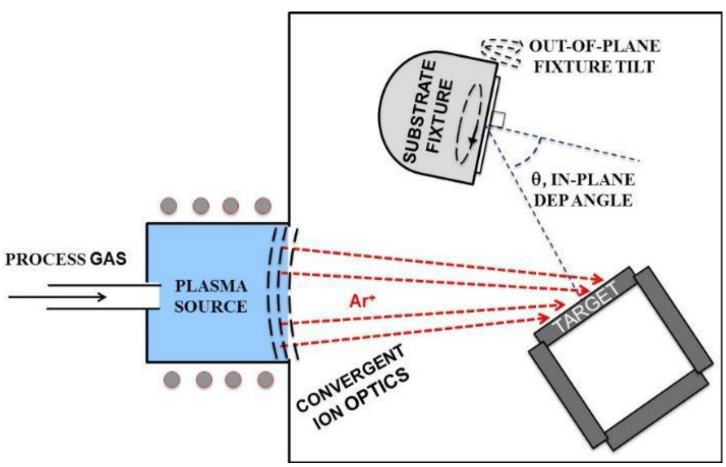

Figure 1: Conceptual illustration of Veeco LDD-IBD equipment for deposition of high-reflectivity Mo/Si layers for EUV mask blanks

Presenting Author

Tania Henry is a Process Development Engineer with Veeco's Advanced Deposition and Etch division. She joined Veeco in 2016, and has over 10+ years of experience in semiconductor materials development. She received a B.A. in Physics from Mount Holyoke College and PhD in Electrical Engineering from Yale University.

P19

Effect of beam-stop on the EUV Ptychography reconstruction

A. Dejkameh, I. Mochi, H. Kim, U. Locans, R. Nebling and Y. Ekinci

Paul Scherrer Institute, Villigen, Switzerland

EUV lithography for semiconductor manufacturing relies on accurate photomask metrology to ensure a high production yield. RESCAN is a lensless actinic patterned mask inspection tool based on coherent diffraction imaging at the Swiss Light Source (SLS). In RESCAN, we use ptychography to recover the sample's complex amplitude from the intensity of its diffraction pattern. RESCAN can perform through pellicle imaging, accurate phase retrieval [1] and currently demonstrated 50 nanometer defect detection (on mask) [2].

In this work, we are exploring the possibility of adding a beam-stop to our data collection routine in order to avoid saturation and blooming effects on RESCAN's detector that may cause the image reconstruction algorithm to converge to an incorrect solution. Pixel masking is a well stablished method in the CDI imaging community to account for the bad detector pixels. However, the limits of affordable data loss has not been systematically investigated yet. Here, we look into the critical factors and elaborate on the physics behind this technique. Furthermore, by providing modulation transfer function (MTF) and mean square error analysis, we estimate the benefits and the limitations of this approach.

[1] I. Mochi, R. Rajeev, et al., Proc. SPIE 10583, Extreme Ultraviolet (EUV) Lithography IX, 105831I (2018). doi: 10.1117/12.2297436
[2] I. Mochi, S. Fernandez, et al., J. Micro/Nanolithography, MEMS, MOEMS, 19(1), 014002 (2020). doi: 10.1117/1.jmm.19.1.014002

Presenting Author

Atoosa Dejkameh graduated from the master program of advanced optical technologies from Friedrich-Alexander University in Germany. Currently, she is a PhD candidate at ETH Zurich and Paul Scherrer Institute. She pursuits the improvement of RESCAN EUV imaging tool by exploring the impact of data loss and techniques to compensate for it on the reconstruction process.

P21

What's new in EUV Lithography Optics at ZEISS? (Invited)

Michael Busshardt, Dirk Juergens, Paul Graeupner

Carl Zeiss SMT GmbH, Germany

For more than 50 years, Moore's Law has driven the steady shrink of feature sizes for integrated circuits. This development has been enabled by resolution improvements of each generation of lithography scanners which generate an image of the lithography mask on the semiconductor wafer. This image contains the patterning information needed to build up an integrated circuit.

A key component of the resolution of every lithography scanner is the optical column consisting of illumination and projection optics. Due to its short operating wavelength of only 13.5nm, EUVL holds the potential for a large gain in resolution. A major challenge is the development and application of advanced optics technology: All optical elements are high precision multilayer-coated mirrors – eventually integrated into full optical systems.

While the NXE:3400C with ZEISS Starlith 3400 optics having a NA of 0.33 is being used for high volume manufacturing by customers, ZEISS extends its EUV roadmap by introducing an advanced NA 0.33 EUV optics to support application of NA 0.33 optics for N3 nodes and beyond.

Furthermore, development of High-NA optics is ongoing and manufacturing of mirrors has already started. This next generation optics consists of a highly flexible illumination system and projection optics with NA 0.55 enabling single-exposure sub 8nm half-pitch resolution to allow scaling beyond the next decade. In this presentation, we will discuss the current status of the EUVL optics development programms both for NA 0.33 and High-NA systems.

Presenting Author

Dr. Michael Bußhardt is a Lead Systems Engineering (SMT-XEEP) staff member of ZEISS Expert Ladder. He received his PhD in Quantum Optics from Ulm University. From 2011-2016, he was a system Engineer (Optics) at Zeiss with main focus on EUV. Since 2016 he is the Lead Systems Engineer for EUV NA 0.33 POB, at Zeiss.

P22

EUV Lithography Design Concepts using Diffraction Optics
(Invited)

Kenneth C. Johnson

KJ Innovation
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This presentation reviews new design concepts for advanced EUV lithography using diffraction optics, building on the maskless EUVL design that was presented at the 2019 Workshop (https://www.euvlitho.com/2019/P22.pdf). The microlens design has been simplified by incorporating chromatic aberration correction in the projection system, and the design approach has been generalized to "holographic" mask-projection lithography using an LPP source, with possible application to Blue-X lithography (λ = 6.7 nm).

Presenting Author

Ken Johnson is a specialist in optical systems modeling and design, with an emphasis on diffraction optics. He has expertise in coupled-wave analysis and simulation of diffraction gratings and periodic structures, and his published research includes potential applications of diffraction optics for maskless lithography and actinic EUV mask inspection and metrology.

P23

EUV-induced Carbon Growth at Contaminant Pressures between 10^{-10} mbar and 10^{-6} mbar: Experiment and Model

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Carbon contamination induced by ultraviolet (UV) radiation affects precision optics in applications as diverse as semiconductor lithography and satellite observations of the Sun. Our previous experiments have shown that low-intensity UV-induced surface contamination depends quasi-logarithmically on the partial pressure of the organic contaminant due to the poly-dispersive nature of the surface-adsorbate system. This complex dependence presents difficulties because, without a physically motivated model, it cannot be extrapolated to low pressures. We present measurements of carbon growth over four orders of magnitude and a physically based model that describes them over that entire range. The model includes a coverage-dependent adsorption energy that we believe can be used to extrapolate to the lower pressures of interest to the Extreme Ultraviolet (EUV) lithography and solar astronomy communities. Our experience with other contaminants leads us to expect that behavior of other organic contaminants will be similar to that of tetradecane. The results also provide insights into the kinetics governing coverage isotherms at extremely low pressures.

Presenting Author

P31

Berkeley MET5 Update

Chris Anderson

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This paper discusses the latest results from the 0.5 NA MET at Berkeley Lab.

Presenting Author

Chris is a versatile engineer, scientist, and manager specializing in Fourier optics, coherence theory, statistical optics, interferometry, statistical data analysis, scientific programming, instrument control programming, and web programming. He also builds innovative music theory books and songwriting software.

P32

Irradiation Systems for Accelerated Testing of EUVL Components

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Fraunhofer ILT has been developing EUV sources for more than 2 decades. In collaboration with Philips and Ushio, ILT has contributed to the development of discharge based sources, which have been operated in the first EUV lithography scanners for chip production.

Having the know-how on EUV sources and their implementation into optical system at hand, ILT has been developing multitude of applications in collaboration with RWTH Aachen University, e.g., EUV laboratory-scale lithography for patterning and resist testing with demonstrated resolution of 28 nm HP or EUV reflectometry for surface sensitive analysis.

The newest member of the family is the Fraunhofer high Irradiance Tool (FIT) for testing of optical components. It is based on our proven FS5440 high power EUV source, whose emission is focused on a sample in controllable atmosphere. Using strong vacuum separation and particle mitigation, a low base pressure following clean, unbiased experimental conditions can be achieved. The expected performance of the FIT includes: EUV irradiance >40 W/cm², angle of incidence on sample <5°, spot diameter >1.8 mm and pulse repetition rate up to 2.5 kHz. The design of the system allows multiplexing to reach 10 kHz and a higher power on sample.

Presenting Author

Jochen Vieker received his Diploma (M. Sc. equiv.) 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 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. He is manager of the R&D projects and architect of ILT's EUV systems. Fields of interest include fundamental research on EUV sources and secondary sources based on laser radiation as well as their applications.

P33

Challenges for the Ultimate Resolution in Photolithography (Invited)

Y. Ekinci

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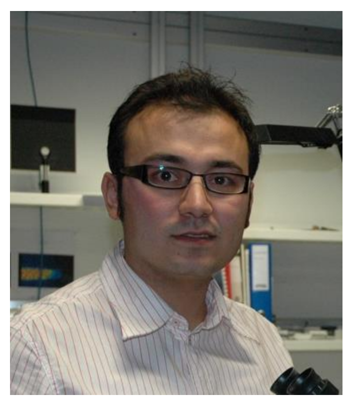
EUV lithography has become the leading lithography technique in semiconductor manufacturing due to its short wavelength and the ability to achieve high-resolution patterning for the current and upcoming technology nodes. Nevertheless, future progress towards the ultimate resolution can be hampered due to the various limitations. Optical resolution limitations are the most obvious one and with high-NA EUVL a significant improvement in resolution will be achieved. Beyond this, reduction of the wavelength will relax the challenging requirement of NA and k values, and therefore lithography at 6.x nm wavelength is proposed as a promising technology, coined as beyond EUV lithography (BEUVL), owing to the availability of sources and multilayer optics. In addition to the optical resolution, other limitations are already emerging, such as photon shot noise, mask 3D effects, and, not the least, resist materials. In this presentation, some of these issues will be addressed, and potential solutions are proposed.

Presenting Author



Yasin Ekinci is head of the Laboratory of Micro and Nanotechnology at Paul Scherrer Institute, Switzerland. He obtained his PhD in Max-Planck Institute for Dynamics and Self-Organization, Göttingen, Germany in 2003. In 2004, he joined Paul Scherrer Institute as a postdoctoral researcher. Between 2006 and 2012 he worked as a postdoctoral researcher and subsequently as a senior scientist and a lecturer in Department of Materials at ETH Zürich. He is at PSI since 2009 working on various topics of nanoscience and technology, including EUV lithography, resist materials, lensless imaging, plasmonics, semiconductor nanostructures, and nanofluidics. He is author/co-author of more than 200 papers and 5 patent applications. He is a fellow of SPIE.

P34

VELOCITY MAP IMAGING OF TEOS AND DEPOSITION ANALYSIS OF FEBID PROCESS IN TEOS

NIGEL MASON and MARIA PINTEA

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Called "the miracle material"(D.N. Payne, SPIE 2020), silica is one of the new generation of materials used for optical fiber, as nanoparticles for medical purposes in cancer treatment and for mask repair and production, "the holy grail" of the electronics industry. We have used $Si(OEt)_4$ or TEOS to deposit silica structure on a surface using the method of Focused Electron Beam Induced Deposition (FEBID), whilst also undertaking a thorough analysis of TEOS electron induced fragmentation using velocity map imaging. The electron beam energy range we used was 0 - 25eV, low electron energy interactions for DEA processes. Experiments are combined with theoretical calculations of electron interactions with TEOS and models of the FEBID process. The present research is part of an ITN wider research project, ELENA (www.elena.hi.is) exploring the dynamics of FEBID and Extreme Ultraviolet Lithography and their development as a methodology for building nanostructures. ELENA is an Initial Training Network funded by the European Union Horizon 2020 program Grant number 722149.

Presenting Author

Maria Pintea, PhD student, School of Physical Sciences, Univesity of Kent; Former: Field Engineer for oilfield service company. Background: Instrumentation and control.

P41

Progress Towards High-NA EUV Photoresists (Invited)

<u>Jara G. Santaclara</u>, Gijsbert Rispens, Ruben Maas, Sander Wuister

ASML, The Netherlands

To further enable cost-effective shrink, both the advances in optical systems and imaging capabilities, as well as the improvements in EUV photoresist are required to lead to practical gains in resolution. In this context, a new High-NA EUV platform is being developed, which features a 0.55 NA and enables 8nm half-pitch (HP) resolution and a high throughput. Despite the fact that the High-NA scanner is yet in development, several tools are currently available for resist understanding and ultimate resolution testing. The later includes exposures using High NA projection tools (like the Berkeley Micro Exposure Tool 0.5NA), and interference lithography tools (Paul Scherrer Institute, PSI). This work gives an overview of the progress and new developments on high resolution photoresists, and shows the current trends regarding key resist parameters, e.g. LWR (Line Width Roughness) and blur.

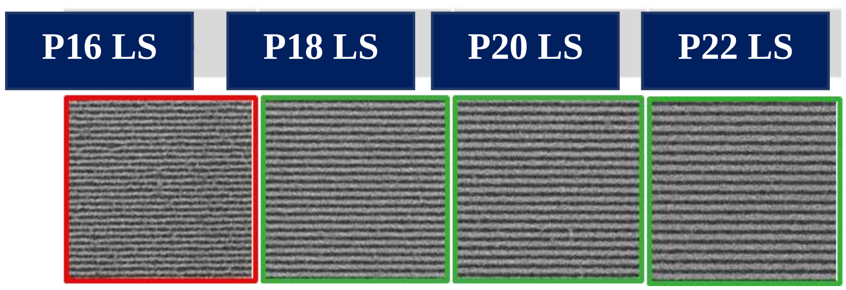


Figure 1. Berkeley Micro Exposure Tool results on ultimate resolution for MOR (Metal-Organic Resist)

Presenting Author

P42

High-NA EUV Lithography Exposure Tool: Advantages and Program Progress (Invited)

Jan van Schoot[1], Eelco van Setten[1], Ruben Maas[1], Kars Troost[1], Jo Finders[1], Judon Stoeldraijer[1], Jos Benschop[1]
Paul Graeupner[2], Peter Kuerz[2], Winfried Kaiser[2]

[1] ASML Netherlands B.V. (The Netherlands)
[2] Carl Zeiss SMT GmbH (Germany)
De Run 6501, 5504 DR Veldhoven, The Netherlands

While EUV systems equipped with a 0.33 Numerical Aperture (NA) lens are being applied in high volume manufacturing, ASML and ZEISS are in parallel ramping up their activities on an EUV exposure tool with an NA of 0.55. The purpose of this so-called high-NA scanner, targeting an ultimate resolution of 8nm, is to extend Moore's law throughout the next decade.

A novel lens design, capable of providing the required Numerical Aperture, has been identified; this lens will be paired with new, faster stages and more accurate sensors enabling the tight focus and overlay control needed for future nodes.

In this paper we will outline the advantages of High-NA, especially for managing the needed extreme low defect printing rates while maximizing the effective throughput for patterning economics. The imaging performance is being simulated based on expected surface figures of the illumination and projection optics. Next to this, an update will be given on the status of the developments at ZEISS and ASML. Buildings, cleanrooms and equipment are being constructed, mirror production is ramping up, many tests are carried out to ensure a smooth implementation.

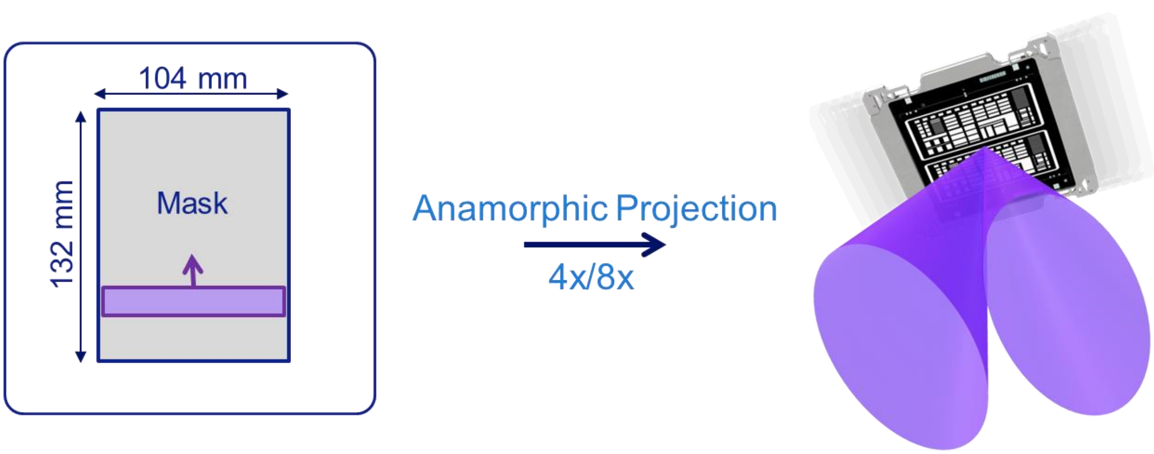


Figure 1: The High-NA exposure tool leaves the mask unchanged by limiting the angles of the light on the mask, despite the larger NA.

Presenting Author

Jan B.P. van Schoot, PhD, Senior Principle Architect at ASML, dept of System Engineering, is based in Veldhoven, The Netherlands.

Van Schoot studied Electrical Engineering at the Twente University of Technology. He received his PhD in Physics, non-linear optics in 1994. After his graduation he held a post-doc position studying waveguide based electro-optical modulators.

He joined ASML in 1996. In 1997 he became Project Leader for the Application of the first 5500/500 scanner as well as its successors up to the 5500/750. In 2001 he became Product Development Manager of Imaging Products (DoseMapper, Customized Illumination). In 2007 he joined the department of System Engineering. He was responsible for the Optical Columns of the NXE:3100 and NXE:3300 EUV systems. After this he worked on the design of the EUV source. He started the High-NA EUV system developments as a study lead, currently he is the main architect for the High-NA optical train.

He holds over 20 patents in the field of optical lithography and presents frequently at conferences about photo lithography.

P43

Fundamental Research of EUV Resist to Resolve the Issues in EUV Lithography (Invited)

Takeo Watanabe

University of Hyogo

As described on the IRDS roadmap, logic foundry producers have used EUV lithographic technology to adapted in HVM from 2019. However, the technical issues remain which are 1) EUV resist which satisfy high resolution, high sensitivity, low LER, and low outgassing, simultaneously, 2) pellicle with high transparency and long lifetime, 3) defect free EUV mask fabrication, and 4) high power and stable EUV light source.

From 1995, EUV R&D was started using NewSUBARU synchrotron light source of University of Hyogo University of Hyogo. Up to now, many significant technology research and development of EUV lithography were done by this research group.

The most significant issue in EUV resist is to achieve low LWR. The spatial distribution of the chemical contents of EUV resist should be uniform. Thus, it is introduced that the soft X-ray resonant scattering method in transmission mode to measure the chemical contents spatial distribution in a EUV resist film. In addition, preventing from the pattern collapse is necessary to achieve high resolution of EUV resist, the adhesion control is needed for the high-resolution achievement. Thus, it is introduced that the layer analysis method in EUV resist film using the soft X-ray resonant scattering method in transmission mode.

Presenting Author

Takeo Watanabe received his Ph.D. from Osaka City University in 1990. He is Full Professor, Director of Center for EUV, and Dean Laboratory of Advanced Science and Technology for Industry, University of Hyogo. He is an expert of the EUV lithographic technology, including optics, exposure tool, mask and resist related technologies. He has authored over 200 technical papers, and he is international affair, and the organizing and program committee members, of the International Conference of Photopolymer Science and Technology (ICPST). He is also Conference Chair of the International Conference of Photomask Japan. And he is a program committee member of the International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN).

P44

Combining EUV Monolayer Resists with Area Selective Depositions (Invited)

Rudy J. Wojtecki*†, Isvar Cordova‡, Jonathan Ma‡, Alexander Hess†
Patrick Naulleau‡ & Greg Wallraff†

† International Business Machines - Almaden Research Center
‡ Center for X-ray Optics at Lawrence Berkeley National Laboratory

The enablement and miniaturization of technologies, such as electronic devices, are largely dependent on patterning materials. Polymer resists in next generation technology nodes face increasingly difficult challenges such as pattern placement without alignment error, low aerial image contrast, low etch resistance and stoichastic defects. We describe a fundamentally different approach to patterning described as additive lithography where the exposure of an organic monolayer is combined with area selective Atomic Layer Deposition (ALD) as the development step, which deposits a high etch resistant metal oxide film for pattern transfer. The imaging tone can be tuned to either positive or negative tone based on different head group chemistries, where positive tone systems use hydroxamic acid derivatives and negative tone silane-based derivatives. The imaging mechanism reveals different two responses to exposure where enhanced inhibition is the result of monolayer crosslinking and thus deposition occurs in unexposed regions and area activation from the generation of polar moieties (Figure 1). Furthermore, synthetic methods enable the modification of hydroxamic acid derivatives where different stearic moieties can be added to the component and show the ability to improve dose sensitivity.

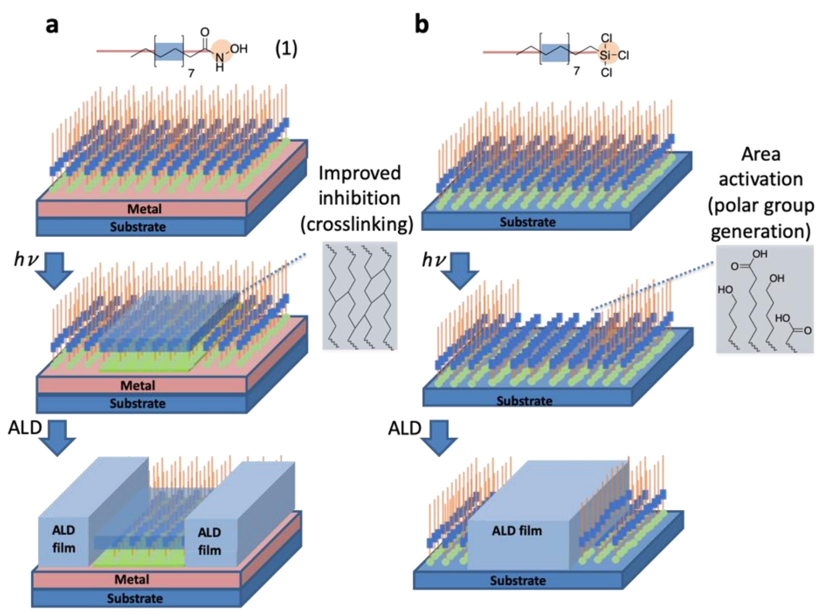


Figure 1: Schematic outline of three approaches to patterning – (**a**) Hydroxamic acid based monolayer crosslinking in response to EUV enabling an area selective deposition and negative tone (**b**) Silane based monolayers resulting in oxidation of exposed regions and area selective deposition resulting in a positive tone.

Presenting Author

Dr. Wojtecki graduated from Case Western Reserve University in 2013 with a Ph.D. in Macromolecular Science & Engineering under the auspices of Stuart J. Rowan (now Univ. of Chicago) and the support of a NASA GSRP fellowship. His graduate research focused on the synthesis of mechanically interlocked polymers composed of catenanes, chemical units that were the subject of the 2016 Nobel prize in chemistry on molecular machines (catenanes & rotaxanes). This work was recently published into the journal ***Science*** in a report titled "Poly[*n*]catenanes: The Synthesis of Molecular Chains." Dr. Wojtecki joined IBM – Almaden Research Center after completion of his graduate work, as an engineer, and promoted to research staff member in 2015. He is author of 20+ peer reviewed scientific publications with more than 1400 citations (h-index 15, i-10 index 16). In 2017 he was recognized as an IBM Master Inventor for work highlighted in over 100 patents and patent applications. Dr. Wojtecki's current research efforts are geared to address materials challenges for self-aligned process technology for the manufacturing of semiconductors and the fabrication of superconducting qubit architectures for quantum computing.

P45

Prescreening of Resists for EUVL from N7 Down to N3 Nodes By EBL and HIM (Invited)

Kenneth E.Gonsalves[b] , Satinder K Sharma[b], Mohamad G. Moinuddin[b], Rudra Kumar[b], Manvendra Chauhan[b], Subrata Ghosh[a]

Indian Institute of Technology at Kamand
[a]School of Basic Sciences [b]School of Electrical and Computer Engineering
Mandi HP 175005, India

Convergent as well as divergent materials design and chemistries have been developed by us for preparing various resist formulations from CARs to non-CARs as well as MOFs, organometallics, organic-inorganic hybrids and activated NP monolayers in an attempt to meet the stringent requirements for EUVL, the all encompassing RLS. Extensive materials characterizations of these resists pre-exposure, are critical and will be discussed along with some photodynamic mechanistic insights. Since EUV photons are still scarce, protocols based on readily available ebl, HIM tools and FESEM/AFM for metrology have been developed in-house for screening the resists for sensitivity, CD, LER/LWR. Patterns with half pitch down to sub 12 nm have been obtained as well as isolated lines of the order of 7 nm. Complex patterns will also be presented. Subsequent EUV exposures are anticipated for calibrating optimum prescreened resists as potential prototypes for fab. The state-of-the-art clean synthesis labs, materials characterization facilities at AMRC, class 100 clean room at C4FED with all relevant major tools ebl, HIM, FESEM, AFM, etch etc are available onsite. International collaborations, particularly with Prof. Weibel, UFRGS & synchrotron Campinas Brazil for EUV photodynamics mechanism studies are ongoing.

Presenting Author

Kenneth E. Gonsalves is Visiting Distinguished Professor at IIT Mandi since Jan 2012 to the present. Prior to that he was the Celanese Acetate Distinguished Professor of Polymer Science at UNC Charlotte, North Carolina USA. He also served as Associate Director S&T oversight for Americas, Office of Naval Research Global from 2009 to 2011. He is the author and or editor of over 300 publications, several books and numerous patents primarily in resist technology. His projects have been funded by NSF, DARPA, DoD, ACS, NCBC and several industry related to resist technology, Intel, Rohm and Haas/Du Pont amongst others. Projects for advanced resists have also been funded by DST, MHRD as well as industry in India. His interests, besides nanoscale resists for NGL, include nanoscale drug delivery focusing on antibiotics, tissue engineering at the nanomicro- scale and organometallic precursors for ceramics. IP and scaleup of advanced resist formulations are anticipated under the TSDP DST commercialization initiatives in linkage with industry.

P46

High Opacity Multi-Trigger Resist (Invited)

C. Popescu[a], G. O'Callaghan[a], A. McClelland[a], J. Roth[c], T Lada[c],
A.P.G. Robinson[a,b]

[a]*Irresistible Materials, Birmingham Research Park, Birmingham, UK*
[b]*School of Chemical Engineering, University of Birmingham, UK.*
[c]*Nano-C, 33 Southwest Park, Westwood, MA, USA.*

It continues to be necessary for there to be substantial improvements in the performance of EUV photoresists in order to meet the lithography requirements for high volume manufacturing. No material currently achieves the combined resolution, sensitivity, and line width roughness (RLS) requirements and furthermore, defectivity issues arising from stochastic effects are becoming increasingly critical as pitches decrease. Whilst traditional chemically amplified resists support the initial insertion, a wide range of materials options are being examined for future nodes [1–3], aiming to identify a photoresist that simultaneously meets RLS and defectivity requirements.

Irresistible Materials (IM) is developing novel resist systems based on the multi-trigger concept. In a multi-trigger resist multiple elements of the resist must be simultaneously activated to enable the catalytic reactions to proceed. In high dose areas the resist therefore behaves like a traditional CAR, whilst in low dose areas, such as line edges, the reaction is second-order increasing the chemical gradient. Effectively there is a dose dependent quenching-like behaviour built in to the resist, enhancing chemical contrast and thus resolution and reducing roughness, whilst eliminating the materials stochastics impact of a separate quencher.

The multi-trigger material previously presented [4-6] consists of a base molecule and a crosslinker, which represent the resist matrix, together with a photoacid generator (PAG). Research has been undertaken to improve this resist, in particular focusing on improving resist opacity and crosslinking density. A non-metal atom has been incorporated into the crosslinker and the results presented here show two iterations of this high opacity crosslinker. To improve the sensitivity, a mark II high-Z crosslinker was synthesised which incorporated longer arms compared to the mark I version, to reduce steric hindrance by increasing the distance of the high opacity atom from the reaction site. Using the PSI exposure tool, a dose-to-size reduction of 65% was found when using the mark II crosslinker and the results are shown in figure 1 and figure 2.
We also present work aimed at improving the LWR of the high opacity resist formulation at high resolution, particularly aimed below 16 nm hp using dense lines when patterned using EUV lithography at the Paul Scherrer Institute, Switzerland. Figure 3 shows 13.3 nm lines on a 14 nm half pitch, with an LWR of 2.97 nm and dose of 26 mJ/cm^2. Figure 4 shows 14.7 nm lines on a 15 nm half pitch, with an LWR of 2.72 nm and dose of 34 mJ/cm^2.
Further, we investigated the effect of the PEB temperature on the performance of these crosslinkers and conducted exposures using an ASML NXE3300 exposure tool. The sensitivity was improved by over 50% when using a 90°C PEB for the mark I and by 20%

for the mark II crosslinker. We present results obtained with the mark II crosslinker demonstrating 16 nm half pitch lines using a 28 nm film thickness with a 90°C PEB and a dose to size of 19 mJ/cm^2, which shows a LWR value of 5.2 nm. Figure 5 shows illustrates the effect of the PEB on the LER of the mark II crosslinker.

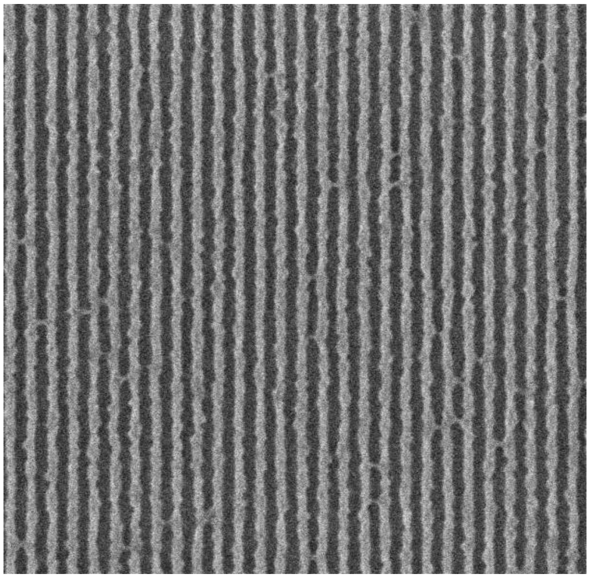


Figure 1: (Mark I high opacity resist) Halfpitch 16 nm, 46 mJ/cm^2, CD 14.2 nm, LWR 6.86 nm

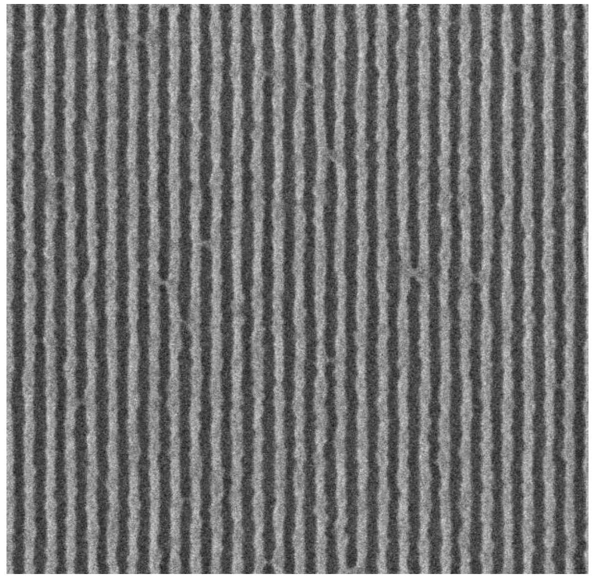


Figure 2: (Mark II high opacity resist) Halfpitch 16 nm, 20.5 mJ/cm^2, CD 14.4 nm, LWR 5.52 nm

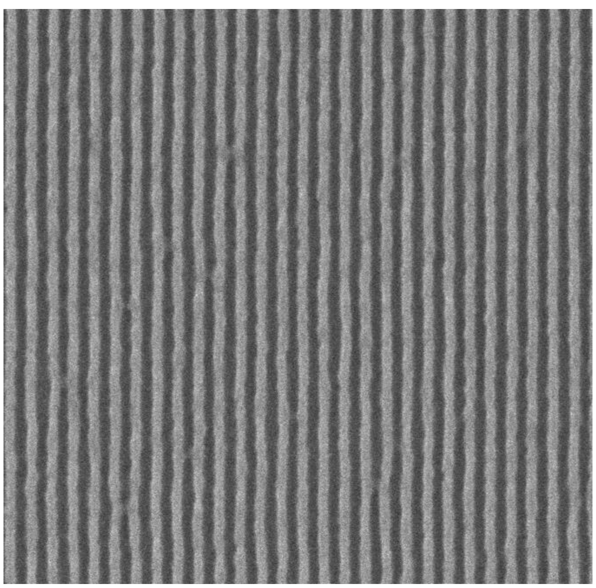


Figure 3: Halfpitch 14 nm, 26 mJ/cm^2, CD 13.3 nm, LWR 2.97 nm, LER 3.01 nm (unbiased, PSI)

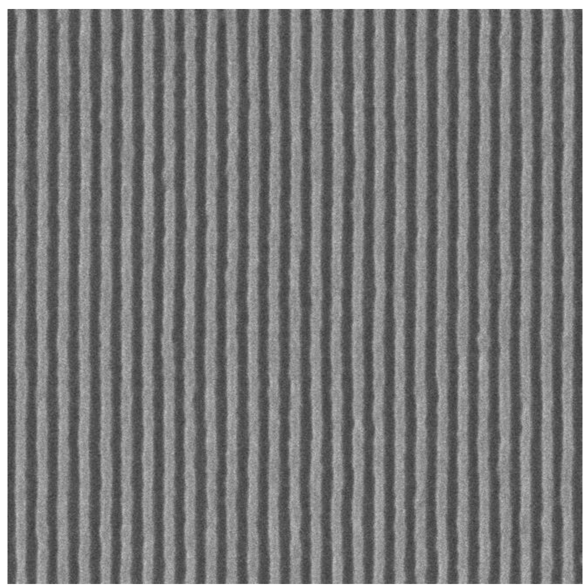


Figure 4: Halfpitch 15 nm, 34 mJ/cm^2, CD 14.7 nm, LWR 2.72 nm, LER 2.45 nm (unbiased, PSI)

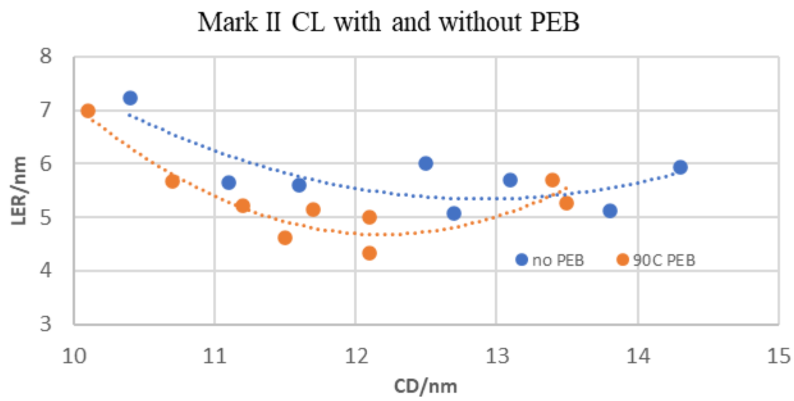


Figure 5: The effect of PEB on the LER of the mark II crosslinker

[1] Stowers, J. K., Telecky, A., Kocsis, M., Clark, B. L., Keszler, D. A., Grenville, A., Anderson, C. N., Naulleau, P. P., "Directly patterned inorganic hardmask for EUV lithography," Proc. SPIE 7969, 796915 (2011)
[2] Krysak, M., Trikeriotis, M., Schwartz, E., Lafferty, N., Xie, P., Smith, B., Zimmerman, P., Montgomery, W., Giannelis, E., Ober, C. K., "Development of an inorganic nanoparticle photoresist for EUV, e-beam, and 193 nm lithography," Proc. SPIE 7972, 79721C (2011)
[3] Cardineau, B., Del Re, R., Al-Mashat, H., Marnell, M., Vockenhuber, M., Ekinci, Y., Sarma, C., Neisser, M., Freedman, D. A., Brainard, R. L., "EUV resists based on tin-oxo clusters," Proc. SPIE 9051, 90511B (2014)
[4] Vesters Y., McClelland A., Popescu C., Dawson G., Roth J., Theis W., de Simone D., Vandenberghe G., Robinson A.P.G, "Multi-trigger resist patterning with ASML NXE3300 EUV scanner," Proc. SPIE **10586**, (2018)
[5] Popescu, C., Kazazis, D., McClelland, A., Dawson, G., Roth, J., Theis, W., Ekinci, Y., Robinson, A.P.G., "High-resolution EUV lithography using a multi-trigger resist," Proc. SPIE 10583, 10583-54 (2018)
[6] O'Callaghan, G., Popescu, C., McClelland,A., Kazazis, D., Roth, J., Theis, W., Ekinici, Y., Robinson, A., "Multi-trigger resist – Novel synthesis improvements for high resolution EUV lithography", Proc. SPIE 10960 (2019)

Presenting Author

Alex Robinson is a Senior Lecturer in School of Chemical Engineering at the University of Birmingham, and is also co-founder, and Chief Technical Officer of Irresistible Materials. He has over twenty years of experience in research in to materials and processes for nanofabrication, including the development of EUV photoresists, and ultrahigh carbon content solution processed films for high aspect ratio plasma etching. Other research interests include the integration of top-down lithography with bottom-up self-assembly of aptamer biosensing molecules for biodetectors, novel nanostructured catalyst via synthetic biology approaches, and investigations of ultra-high Stokes shift organic fluorescent materials for bio-imaging applications.

P47

High Fluorinated Molecular Resists Working under Electron-beam and Extreme UV Irradiation (Invited)

Hyun-Taek Oh,[1] Kanghyun Kim,[2] Sangsul Lee,[2] Jin-Kyun Lee*[1]

[1] Polymer Science and Engineering, Inha University, Incheon 22212, South Korea.
[2] Pohang Accelerator Laboratory, POSTECH, Pohang 37673, South Korea.

Extreme UV lithography (EUVL) is entering slowly the stage of commercial production beyond the feasibility study level. To keep abreast with this progress, it is necessary to provide resist materials capable of maximizing the usefulness of EUV photons and settling down the stochastic issues. In this presentation, we propose a concept of single molecule-based EUV resists that do not require sub-stoichiometric auxiliaries. Based on previous results with highly fluorinated polymers, we designed amorphous molecular structures equipped with perfluoroalkyl ether (PFAE) chains or fluoroarenes. Successful coupling reactions between phenolic cores and perfluoroalkyl vinyl ethers or fluoroarenes provided the molecular resists, which were evaluated in terms of imaging behaviour and working mechanism under e-beam and EUV lithographic conditions. Solubility of the thin molecular films decreased by those high energy radiations, and thus negative-tone patterns down to 30 nm half pitch could be obtained after developing in fluorous solvents. This unique imaging protocol based on fluorine and radical chemistry may open new pathways to high performance EUV resists hopefully in near future.

Presenting Author

J-K Lee is a professor in Inha University (South Korea) since 2010. After his Ph.D study in chemistry in the University of Cambridge (2005) and postdoctoral research in Cornell University (2010), he has been studying fluorous materials chemistry and photoresists based on his expertise in organic synthesis. His main research interest is molecular EUV resists, patterning materials for high resolution OLED displays and fluorinated functional polymers.

P48

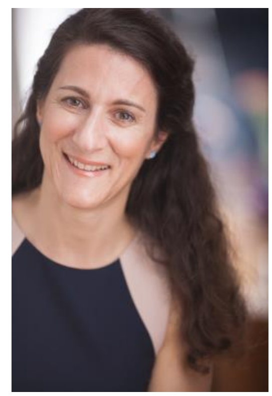
EUV Resists: What's the Road to High NA? (Invited)

Anna Lio

Intel Corporation

Extreme Ultraviolet Lithography (EUVL) at 13.5 nm wavelength is now in High Volume Manufacturing (HVM). To achieve the highest resolution with stochastics control on current 0.33 NA, future 0.55 NA tools and extend EUV into the future many challenges remain. Photoresist performance remains central to realizing the full potential of EUVL. In this paper we discuss considerations for current and future EUV resist development.

Presenting Author



Dr. Anna Lio is a Senior Principal Engineer at Intel Corporation, Portland Technology Development. She manages the development of all EUV lithography materials for Intel's current and next generation technologies. Prior to that she led the development of lithography processes for Intel's revolutionary trigate transistor process technology at the 22 nm node. She joined Intel in 1997 and has worked in the area of photoresist, design rules definition, microprocessor process development and integration for every Intel's technology starting at the 130nm node. Anna holds a M.S. in Physics from the University of Pisa (Italy) and a PhD in Electrical Engineering from the University of Glasgow (UK). During her PhD, she was a visiting scholar at the Materials Sciences Division at LBNL in Berkeley, CA – an experience that ultimately shaped her personal and professional life. Anna is passionate about empowering women in science and engineering and is an active mentor at the corporate, college and high school level.

P49

Flood Exposure Assisted Chemical Gradient Enhancement Technology (FACET) and Stochastic Aware Resist Formulation and Process optimizer (SARF-Pro) for EUV Lithography (Invited)

Seiji Nagahara

Tokyo Electron Limited, Tokyo, Japan

The enhancement of chemical gradients during the formation of patterns in EUV resists is beneficial for higher resist resolution, better process windows for improved CD control, and lower resist roughness. These improvements are helpful for enhancing resist sensitivity and reducing resist defectivity due to EUV stochastic issues. In this talk, Flood Exposure Assisted Chemical Gradient Enhancement Technology (FACET) by using UV flood exposure technology after EUV exposure will be introduced. The mechanism of the process window improvement by FACET will be explained. To balance chemical gradient enhancement and stochastic effects, Stochastic Aware Resist Formulation and Process optimizer (SARF-Pro) with a fast-stochastic simulation model is created. The optimization results of SARF-Pro for EUV resists and processes will be discussed.

Presenting Author

Seiji Nagahara is Principal and Chief Scientist in Tokyo Electron Ltd (TEL). He now works for marketing and development of the next generation coater and developer equipment in TEL. Prior to joining TEL, he was a lithographer in Renesas Electronics, NEC Electronics, and NEC. He researched lithography related technologies in a variety of places including IMEC (Belgium), University of California, Berkeley (USA), Argonne National Laboratory (USA), EIDEC (Japan) and Toshiba (Japan) in addition to TEL. His previous R&D topics include broad topics in lithography and Directed Self-Assembly (DSA) technologies. He took Bachelor, Master, and Ph.D. degrees in Engineering at Osaka University, Japan. He was a Research Fellow of the JSPS at Osaka University. He is active as an author of technical papers, book chapters, and patents in patterning technologies. He also contributes to the academic and technical societies as a committee member.

P50

Determination of Effective Attenuation Length of Slow Secondary Electrons in Polymer Films

Oleg Kostko,[1,2,3] Jonathan H. Ma,[3,4] and Patrick Naulleau,[3]

[1]Chemical Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 (USA)
[2] Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 (USA)
[3] Center for X-ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 (USA)
[4] Department of Physics, University of California, Berkeley, CA 94720 (USA)

Slow electrons (with energy below 10 eV) play an important role in nature and technology. For instance, they are believed to initiate solubility change in extreme ultraviolet (EUV) resists. Depending on their mobility, such secondary electrons can lead to image blur and degradation of patterning resolution. Hence, it is important to characterize the transport of slow electrons by measuring parameters such as the effective attenuation length (EAL). We present a technique that allows for prompt characterization of EAL in polymer films. In this experiment, slow electrons are generated in a substrate upon absorption of X-ray photons. The attenuation of electron flux by a polymer film is measured as a function of the film thickness, allowing for the determination of EAL for slow secondary electrons. We illustrate this method with poly (hydroxy styrene) and poly (methyl metacrylate) films. Furthermore, we propose an improvement for this technique that would enable the measurement of EAL as a function of electron kinetic energy.

Presenting Author

Oleg Kostko is a scientist at the Chemical Sciences Division, Berkeley Lab, where he leads an effort for developing novel spectroscopies on nanoscale systems. Most of his research involves utilization of VUV, EUV, and soft X-ray radiation generated by the Advanced Light Source.

P51

Vapor-Phase Infiltration Synthesis of Organic-Inorganic Hybrid Nanocomposite Resists Towards EUVL (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

Metal-containing organic-inorganic hybrid resists in principle can offer high EUV absorption with increased etch resistance. To optimize the eventual resist exposure characteristics and other performance parameters, it is critical to readily control the type of incorporated inorganic element and resist composition, which is non-trivial for the typical chemical synthesis. In this talk, I will overview the new hybrid resist synthesis approach based on the vapor-phase infiltration, a technique derived from atomic layer deposition (ALD), where the cyclically exposed gaseous organometallic precursors infiltrate and become hybridized with the organic thin film matrix. The initial electron lithography study of alumina-infiltrated PMMA demonstrates fully controllable electron exposure characteristics and etch resistance, enabling extremely high Si etch selectivity far exceeding known commercial positive-tone resists. Also briefly discussed is the preliminary investigation of the exposure and development characteristics of infiltrated hybrid resist based on low-energy (~80 eV) electron beam, emulating the EUV exposure process. Given the easy implementation combined with versatile ex-situ control of resist characteristics, the ALD-based hybrid resist synthesis approach has a potential for enabling the resist performance required for advanced lithography technologies such as EUVL.

Presenting Author

Chang-Yong Nam is a Scientist 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. Chang-Yong received his Ph.D. in Materials Science and Engineering from University of Pennsylvania (2007), M.S. in Materials Science and Engineering from KAIST (2001), and B.E. in Metallurgical Engineering from Korea University (1999; leave of absence for military service during 1995 – 1997). Chang-Yong joined BNL in 2007 as a Goldhaber Distinguished Fellow and has risen through the ranks to Scientist in 2016. His current research addresses two focused areas: (a) Development and application of ALD techniques toward the materials innovation in nanopatterning, hybrid nanocomposite, nanoelectronics, and catalysis; (b) Materials processing and device physics in organic semiconductors and low-dimensional materials including nanowires and two-dimensional materials. His awards include BNL Spotlight Awards (2018, 2011) and Goldhaber Distinguished Fellowship (2007).

P61

Tin Plasma Driven by a 2-μm-Wavelength Laser (Invited)

O.O. Versolato

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Department of Physics and Astronomy, and LaserLaB, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands

Tin-microdroplet laser-produced plasma is employed to generate extreme ultraviolet (EUV) light for nanolithography. Currently, CO_2-gas lasers operating at 10 μm wavelength are used in the industry to drive the plasma. Solid-state lasers operating at shorter, mid-infrared wavelengths may present a viable alternative and may offer some key advantages. In our experiments we compare plasma generated by a Nd:YAG laser, operating at its fundamental wavelength λ = 1 μm, to one generated by a Nd:YAG-pumped master oscillator power amplifier (MOPA), operating at λ = 2 μm wavelength. Spectroscopy of the laser-produced plasma is performed using a broadband transmission-grating spectrometer. We present and compare Sn-plasma EUV emission spectra produced by the two laser systems from a planar solid target. The 2-μm-wavelength-laser-driven plasma is found to create a significantly larger conversion efficiency.

Presenting Author

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P62

Physics of Operation of Energetiq Source (Tentative Title) (Invited)

Steve Horne

Energetiq

Presenting Author

P63

Update of >300W High Power LPP-EUV Source Challenge for Semiconductor HVM (Invited)

Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Hiroshi Tanaka, Yukio Watanabe, Tsukasa Hori, Yutaka Shiraishi, Tatsuya Yanagida, Georg Soumagne, Tsuyoshi Yamada and Takashi Saitou

Gigaphoton Inc. Hiratsuka facility
3-25-1 Shinomiya Hiratsuka Kanagawa, 254-8567, JAPAN

Gigaphoton develops CO_2-Sn-LPP EUV light source which is the most promising solution as the13.5nm high power light source for HVM EUVL. Unique and original technologies including; combination of pulsed CO_2 laser and Sn droplets, dual wavelength laser pulses for shooting and debris mitigation by magnetic field have been applied. We have developed first practical source for HVM; "GL200E" [1)] in 2014. Then it is demonstrated which high average power CO2 laser more than 20kW at output power in cooperation with Mitsubishi Electric[2)]. Pilot#1 is up running and it demonstrates HVM capability; EUV power recorded at 111W on average (117W in burst stabilized, 95% duty) with 5% conversion efficiency for 22 hour operation in October 2016[3)]. Availability is achievable at 89% (2 weeks average), also superior magnetic mitigation has demonstrated promising mirror degradation rate (= 0.5%/Gp) at 100W or higher power operation with dummy mirror test.

We have demonstrated >300W operation data (short-term) and actual collector mirror reflectivity degradation rate is less than 0.15%/Gp by using real collector mirror around 125W (at I/F clean) in burst power > 10 Billion pulses operation[4)]. Also we will update latest challenges for >250W average long-term operation with collector mirror at the conference.

REFERENCE

1) Hakaru Mizoguchi, et. al.: "Sub-hundred Watt operation demonstration of HVM LPP-EUV source", Proc. SPIE 9048, (2014)
2) Yoichi Tanino et.al.:" A Driver CO2 Laser Using Transverse-flow CO2 Laser Amplifiers", EUV Symposium, 2013, (Oct.6-10.2013, Toyama)
3) Hakaru Mizoguchi, et al: " High Power HVM LPP-EUV Source with Long Collector Mirror Lifetime", EUVL Workshop 2017, (Berkley, 12-15, June, 2017)
4) Hakaru Mizoguchi et al.:" Challenge of >300W high power LPP-EUV source with long collector mirror lifetime for semiconductor HVM", Proc. SPIE 11323, Extreme Ultraviolet (EUV) Lithography XI (2019) [11323-28]

Presenting Author

Hakaru Mizoguchi is a Senior Fellow in Gigaphoton Inc., Fellow of The International Society of Optical Engineering (SPIE), and member of The Laser Society of Japan and The Japan Society of Applied Physics. He received a diplomat degree in plasma diagnostics field from the Kyushu university, Fukuoka, Japan in 1982 and join Komatsu ltd. He joined CO2 laser development program in Komatsu for 6 years. After that he was a guest scientist of Max-Plank Institute Bio-Physikalish-Chemie in Goettingen in Germany 2 years, from 1988 to 1990. Since 1990 he concentrated on KrF, ArF excimer laser and F2 laser research and development for lithography application. He was general manager of research division in Komatsu Ltd. until 1999. He got PhD degree in high power excimer laser field from Kyushu university in 1994. In 2000 Gigaphoton Inc. was founded. He was one of the founders of Gigaphoton Inc.. From 2002 to 2010 he organized EUV research group in EUVA program. Now he is promoting EUV light source product development with present position. He got Sakurai award from OITDA Japan in 2018.

P64

Simulations of Laser-Driven EUV Sources – the Impact of Laser Wavelength (Invited)

Steven Langer, Howard Scott, Tom Galvin, Emily Link, Brendan Reagan, and Craig Siders

Lawrence Livermore National Laboratory

Future generations of integrated circuits will have smaller features and are likely to need a shorter wavelength EUV source. Continuing to use CO2 lasers is a possibility, but the high electrical power they consume is a significant issue. We investigate whether more efficient, all solid-state lasers are a viable alternative that will deliver high conversion efficiency (CE) as well as better overall efficiency. The simulations discussed in this talk focus on CE at 13.5 nm, but we also look at shorter wavelength EUV sources.

The results of 1D HYDRA ensemble simulations of the CE of laser-heated targets will be presented. The ensembles vary two parameters – the laser intensity and the laser wavelength (between 1 and 12 μm). HYDRA is a radiation-hydrodynamics code developed to simulate inertial confinement fusion experiments at the National Ignition Facility and other large laser facilities. Physical variables are only functions of the laser direction in a 1D simulation, but that is enough to capture the key properties of a laser heated EUV source. The Merlin workflow framework allows us to easily run a thousand HYDRA simulations in a two-parameter study using a modest amount of computer time. If more computer time is available, the same approach can be used to run 1D ensembles with more parameters or to run 2D ensembles. These results allow us to gain insight into which laser wavelengths are attractive for future EUVL sources. Our simulations also provide insight into the physics and computational aspects that are crucial to accurately modeling the CE of these plasma sources.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344 and was supported by the LLNL-LDRD Program under20-ERD-006. LLNL-ABS-807638.

Presenting Author

Steven Langer received his PhD from the Dept. of Applied Physics at Stanford University for work on computational astrophysics. He has worked on a variety of topics related to Inertial Confinement Fusion at LLNL since 1985. Steve uses massively parallel computers to simulate experiments carried out using the National Ignition Facility Laser at LLNL. Steve also develops massively parallel physics simulation codes and has participated in setting requirements for large computer systems at LLNL.

P65

High-power EUV Light Source Based on Steady-state Microbunching Mechanism

Xiujie Deng

Tsinghua University, Beijing, China (On behalf of the SSMB Task Force)

Steady-state microbunching (SSMB) in electron storage rings implies a longitudinal bunch structure defined by an optical or ultraviolet wavelength, typically six or more orders of magnitude smaller than a conventional radiofrequency wavelength. The strong coherent radiation from microbunched beams and the intrinsic high repetition rate of storage ring can combine to support a facility with high-average-power, high-repetition-rate or continuous-wave, narrow-band, and short-wavelength radiation, which is a promising candidate to fulfill the need of high-power EUV source for the high volume manufacturing of EUV lithography. An initial task force has been established at Tsinghua University, in collaboration with researchers from China, Germany, the USA, and elsewhere, to promote SSMB research with the goal of developing an EUV SSMB storage ring. In this talk, the concept of SSMB as well as the potential advantages of applying it for EUV lithography are briefly reviewed. The main tasks of the collaboration at this moment, which consist of proving the SSMB working mechanism, the dedicated magnet lattice design for EUV SSMB storage ring, the efforts to address related technical challenges, are then presented, with emphasis on the recent important success of the SSMB proof-of-principle experiment conducted at the Metrology Light Source (MLS) in Berlin.

The SSMB PoP Experiment Collaboration:
Tsinghua University: Alex Chao, Xiujie Deng, Wenhui Huang, Chuanxiang Tang*, Lixin Yan
Helmholtz-Zentrum Berlin (HZB): Jörg Feikes*, Arnold Kruschinski, Ji Li, Aleksandr Matveenko, Yuriy Petenev, Markus Ries
Physikalisch-Technische Bundesanstalt (PTB): Arne Hoehl, Roman Klein

Related work:
[1] Xiujie Deng, Alex Chao, Jörg Feikes, Arne Hoehl, Wenhui Huang, Roman Klein, Arnold Kruschinski, Ji Li, Aleksandr Matveenko, Yuriy Petenev, Markus Ries, Chuanxiang Tang and Lixin Yan, First Experimental Demonstration of the Mechanism of Steady-state Microbunching, under review.

Presenting Author

Xiujie Deng is an accelerator physics Ph.D. student at Tsinghua University, Beijing, China. He received the B.S. degree from Tsinghua University in 2015. His current work focuses on the physics of a novel mechanism called steady-state microbunching (SSMB), based on which high-power short-wavelength coherent radiation at a high repetition rate or in continuous-wave mode can be produced using electron storage rings.

P66

High Average Power Solid-State Lasers for driving Next Generation EUV Sources (Invited)

Brendan Reagan, Tom Galvin, Steven Langer, Craig Siders, Emily Sistrunk, and Thomas Spinka

Advanced Photon Technologies
Lawrence Livermore National Laboratory

Extreme ultraviolet lithography based on Sn laser-produced plasmas driven by λ = 10.6μm CO_2 lasers entered high volume manufacturing for critical layers in 2019. However, increases in EUV source power and overall efficiency are desired for future implementations. The Big Aperture Thulium (BAT) laser concept, originally developed by LLNL for driving compact laser-based particle accelerators, constitutes a viable path towards hundreds of kilowatts to megawatts average power, pulsed lasers. Based on directly diode-pumped solid-state amplification, these λ≈2μm lasers exploit the long upper level lifetime of thulium-doped materials to operate with unmatched efficiency for high energy, pulsed lasers. The results of recent efforts aimed at using this laser concept to optimize the overall efficiency, wall plug to EUV photons, will be presented. The next steps for demonstrating the feasibility of this technology as an EUV driver will also be discussed.

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Presenting Author

P72

A SHARP Look at EUV Masks from a Different Angle

Markus Benk, Weilun Chao, Ryan Miyakawa, Kenneth Goldberg,Patrick Naulleau

CXRO, LBL

SHARP is a synchrotron-based EUV photomask microscope. It emulates the mask-side numerical aperture, imaging conditions and illumination settings of current and future EUV lithography scanners. We are upgrading the SHARP microscope with more anamorphic zoneplates and a fast image sensor.

In addition to zoneplates at 6º chief-ray angle, we have installed anamorphic zoneplates at 5.355º chief-ray angle. These zoneplates are available with and without a central obscuration of 0.2 σ, allowing to study the effect of the central obscuration on the image. Zoneplates with an azimuthally rotated plane of incidence are available for comparing image formation at the edge of the slit to the center.

We are taking delivery of the fast image senor this summer. The senor enables additional data acquisition modes on SHARP. Recording a continuous focus stack allows for computing through-focus series at arbitrary step size and focus position as well as computationally removing the tilted focal plane from the image. Image data with source-angular resolution allows for synthesizing images at an arbitrary pupil fill.

We provide an overview of the SHARP microscope and its key components. We present image data recorded with the anamorphic zoneplates and demonstrate data acquisition modes for the fast image sensor.

Funding for SHARP operations is provided by Intel. General EUV infrastructure at Berkeley is funded through the EUREKA program. This work is performed by University of California, Lawrence Berkeley National Laboratory under the auspices of the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.

Presenting Author

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

P73

Approaches for EUV Mask Phase Imaging

Ryan Miyakawa

CXRO, LBL

As EUV lithography moves into its next generation, the understanding and characterization of three-dimensional (3-D) mask effects including telecentricity errors, contrast fading, and best focus shifts are becoming increasingly important. While rigorous mask modeling has played an important role in developing novel mask designs, it is equally important to develop the proper metrology to validate that these masks are operating according to design. This is especially true in the case of EUV phase shift masks, where small deviations in absorber height or etch depth can adversely impact the performance of the mask. While atomic force microscopes (AFMs) can be used to measure absorber and etch profiles, they cannot directly measure the EUV phase, which may be influenced by other factors including absorber shadowing, illumination angle of incidence, and near-field electromagnetic effects that may be pitch-dependent. CXRO is currently investigating both novel direct phase imaging techniques based on exotic pupil functions, as well as iterative techniques such as Fourier ptychography. In this presentation we report on the ongoing progress of these studies.

Presenting Author

Ryan Miyakawa is a research scientist at CXRO specializing in EUV optical system modeling and design. After receiving his Ph.D. from UC Berkeley in 2011, Ryan's work has focused on the development wavefront sensors for next-generation EUV systems including the MET5 shearing interferometer, the AIS wavefront sensor on SHARP, and the zone plate test stand (ZTS).

P74

Probing Multilayer, Absorber, and 3D Phase Effects in EUV Masks

Stuart Sherwin

CXRO, LBL

With growing interest in EUV attenuated phase-shift masks due to their superior image quality for certain applications, measuring both the intensity and phase of EUV reflected from the mask is becoming critical. We present a suite of actinic measurement modalities performed at CXRO including hyperspectral reflectometry, hyperspectral scatterometry, and computational Zernike phase contrast imaging. We compare the capabilities of each modality to capture information critical to lithography, including thin-film and mask 3D effect

Presenting Author

Stuart Sherwin received his Bachelor's in Physics and Applied Mathematics from UC Berkeley in 2013. Following an interlude at KLA, in 2016 he returned to UC Berkeley once again to pursue a PhD in Electrical Engineering and Computer Science. Under the direction of Laura Waller, Andy Neureuther, and Patrick Naulleau, his main research focuses are Computational Imaging and EUV Lithography.

P75

Depth profiling with Standing Wave X-ray Photoemission Spectroscopy

S. Nemšák

Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley CA, USA

Quantitative depth analysis is one of the most desired information obtained in photoemission experiments. Depth profiling using the "conventional" X-ray photoemission spectroscopy usually involves a use of a few different photon energies and/or emission angles to vary the effective information depth. However, in order to obtain a fully quantitative image of the studied system, several theoretical, semi-empirical and experimental quantities are needed, which quite often is not the case.

There is an alternative solution to the problem — standing-wave (ambient pressure) X-ray photoemission spectroscopy — a recently developed experimental tool possessing a huge application potential due to its superb depth resolution [1,2]. Examples relevant to the EUV lithography process, such as depth profiling of the photoresist, will be discussed.

[1] S. Nemšák, A. Shavorskiy, O. Karslioglu, I. Zegkinoglou, A. Rattanachata, C.S. Conlon, A. Keqi, P.K. Greene, E.C. Burks, F. Salmassi, E.M. Gullikson, S.-H. Yang, K. Liu, H. Bluhm, C.S. Fadley, *Nat. Comm.* **5**, 5441 (2014)
[2] O Karslıoğlu, S Nemšák, I Zegkinoglou, A Shavorskiy, M Hartl, F Salmassi, EM Gullikson, ML Ng, Ch Rameshan, B Rude, D Bianculli, AA Cordones, S Axnanda, EJ Crumlin, PN Ross, CM Schneider, Z Hussain, Z Liu, CS Fadley, H Bluhm, *Faraday Discussions* **180**, 35 (2015)

Presenting Author

Slavomir Nemsak joined the Berkeley Lab as a postdoc in 2011 working in the group of Prof. Fadley. In 2014 he became a group leader in Forschungszentrum Juelich and was in charge of photoelectron microscopy beamline at BESSY-II in Berlin. Since 2017 he is a staff scientist at the Advanced Light Source working at soft and tender X-ray ambient pressure photoemission beamlines.

P76

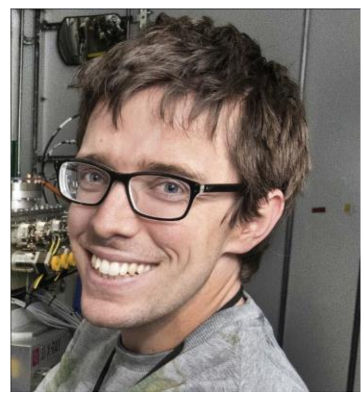
Critical Dimension GISAXS:
Application using soft, tender and hard x-rays

Guillaume Freychet

CXRO, LBL

We have developed a high-performance Grazing Incidence SAXS simulation tool to reconstruct the in-depth profile highly ordered material such as line gratings. Here, we will present the latest development and applications of the technique using hard x-rays on line gratings and contact holes. Moreover, the CD-GISAXS approach was extended to study line edge roughness, latent images and lamellae structure of diblock copolymers, taking advantage of the full energy range provided at the advanced light source and the National Synchrotron Light Source II and more specifically of the chemical sensitivity provided by soft and tender x-rays scattering.

Presenting Author



Guillaume Freychet got his PHD in material science at the CEA institute in Grenoble France in 2016. He worked 2 years at the Advanced Light Source in Berkeley as a postdoctoral fellow and is now a beamline scientist at the Soft Matter Interfaces beamline (12-ID) at the National Synchrotron Lightsource II (NSLS-II) at Brookhaven National Laboratory, Upton NY, USA. His expertise is in the development of new synchrotron-based techniques and analysis methodologies, with a particular focus on tender X-ray scattering. He also has experience in programming and software development for both on-the-fly data analysis and visualization. He is also currently playing an import role in the development of resonant x-ray scattering analysis tools.

P77

Characterization Techniques for Polymer Interfaces using Visible and Infrared Photons

M. Salmeron

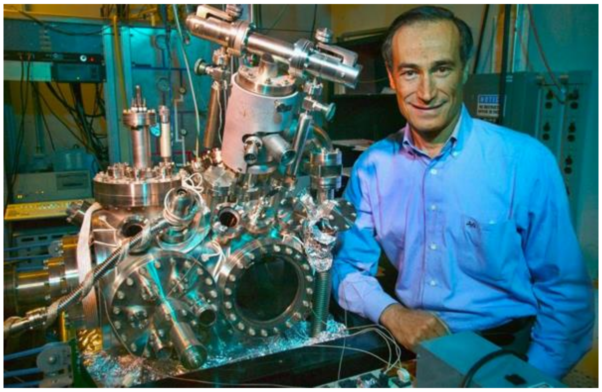
Materials Science Division. Lawrence Berkeley National Laboratory

As semiconductor chip manufacturing pushes towards the nm scale size, understanding photoresist patterning and its resolution limits requires characterizing techniques of the structure and composition before and after irradiation with similar or better spatial resolution. I will present two optical techniques that can provide the desired interface sensitivity with minimal perturbation of the polymeric materials. One is tip-enhanced Fourier Transform Infrared Spectroscopy, or nano-FTIR for short. The other is Sum Frequency Vibration Spectroscopy, or SFVS.

In nano-FTIR the diffraction limit of IR light is overcome by using the plasmon resonance effect, where the IR field excites collective electron oscillations inside a sharp metal tip of nm radius, as in an Atomic Force Microscopy. The local field created by the oscillating charge is orders of magnitude larger near the tip than in the incoming or outgoing photon, and decays exponentially away from the tip apex. This makes possible to obtain simultaneous topographic AFM images and IR spectroscopic images of the material with nm spatial resolution. Topographic resolution in the x,y plane is provided by the sharpness of the tip, while the exponential decay of the plasmonic field away from the tip apex provides nm resolution in the z-direction (perpendicular to the interface).

The second technique, Sum Frequency Vibrational Spectroscopy (SFVS), based on a non-linear excitation and emission effect when a material is simultaneous excited (in time and space) by visible and infrared photons. The IR excites vibrations in the molecular groups while the visible photon brings the excited state to a higher energy level (as in Raman spectroscopy). This second order process has non-zero amplitude only when the material has no inversion symmetry, which for most materials means the interface. For example, the terminal CH3 group of a straight alkyl chain on a surface is easily excited, while the CH2 groups inside the chain have opposite symmetries and the mode becomes inactive, except if the chain bends forming a kink. Even for materials made of asymmetric molecules, they are symmetric when disordered in liquid or amorphous phase, because in the coherence volume of the light wavelength the molecules are randomly (i.e., isotropically) oriented.

Presenting Author



Prof. M. Salmeron is a Senior Staff Scientist in the Materials Science Division of the Lawrence Berkeley National Laboratory and Adjunct Professor in the Materials Science and Engineering Department at the University of California, Berkeley. His research focuses on fundamental studies of materials surfaces, including structure, chemical, electronic, and mechanical properties. During his career he has developed many instruments and methodologies that make possible in situ studies of surfaces in gas and liquid environments, including: High Pressure Scanning Tunneling Microscopy, Ambient Pressure Photoelectron Spectroscopy, and X-ray Absorption Spectroscopy.

P78

Understanding EUV Electron Driven Processes —a Progress Update

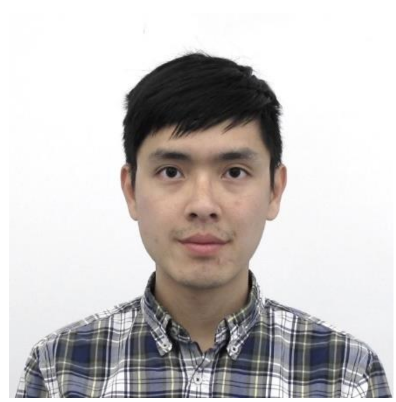
Jonathan H. Ma, Han Wang, David Prendergast, Oleg Kostko, Andrew Neureuther, and Patrick Naulleau

CXRO, LBL

Resist has emerged to be the biggest challenge for EUV lithography. Part of the challenge is the novel exposure chemistry. Unlike DUV, where photochemistry drives solubility switching, EUV chemistry is driven by a cascade of secondary electrons. Understanding electron-initiated chemistry is vital for rational design of EUV materials. We approach this problem both experimentally and computationally. From EUV electron yield measurement, we see evidence of electron capture upon the addition of photo acid generators (PAGs). We observe changes in electron yield as a function of dose received. The implications of the observations will be discussed. On the other hand, with density functional computations, we can understand electron related processes at a molecular level. Internal excitation and electron attachment induced fragmentation are investigated by ab initio molecular dynamics calculations. Comparisons with literature report on PAGs yield useful insights. Relative importance of internal excitation and electron attachment will be discussed. We will demonstrate that computation techniques can be used to explain, and in the near future, engineer mechanistic selectivity. Similar techniques can be applied to metal oxide-based systems as well. Using the prototypical organotin compound as an example, we discovered that different excitation mechanisms would lead to chemical outcome, providing leverage for engineering mechanistic selectivity.

Presenting Author

Jonathan Ma is a graduate student at the Center of X-ray optics working with Dr. Patrick Naulleau and Dr. Adny Neureuther. He is completing his PhD in physics at UC Berkeley with a focus in EUV materials and fundamental processes. He has performed EUV related spectroscopic work and is also working on computational chemistry-based approach to understand EVU processes, facilitating rational design of EUV materials.



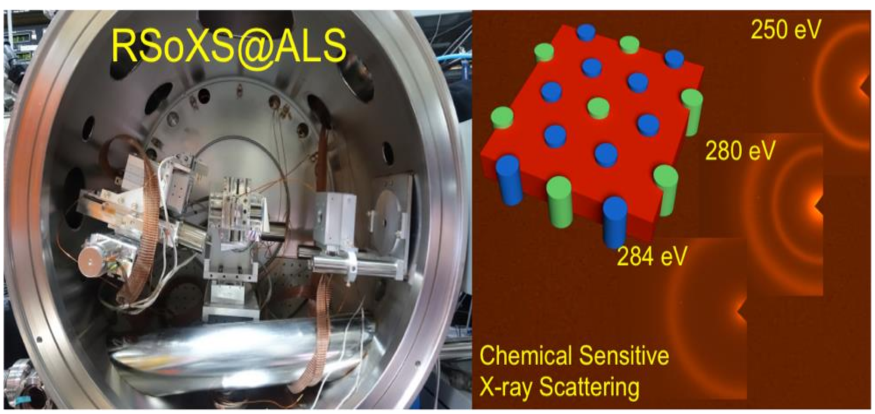
P79

CONRAST ENHANCEMENT FOR SOFT MATERIALS WITH RESONANT SOFT X-RAY SCATTERING

Cheng Wang

Advanced Light Source, Lawrence Berkeley National Laboratory

An improved understanding of fundamental chemistry, morphology, and dynamics in polymers and soft materials requires advanced characterization techniques that amenable to in situ and in operando studies. Soft X-ray methods are especially useful in their ability to non-destructively provide material or chemical moiety specific information. Recent development of resonant soft x-ray scattering (RSoXS) at the Advanced Light Source (ALS) has enabled its applications to many critical research areas of materials research. Combining conventional x-ray scattering with soft x-ray absorption spectroscopy, RSoXS is a unique chemical sensitive structure probe that provides a novel route to unambiguously decipher the complex morphologies of mesoscale materials. Tuning x-ray photon energies to match the absorption spectrum of the different chemical components, the scattering contributions from the different components can be selectively enhanced, enabling a glimpse into these complex morphologies with unprecedented details. Applications of RSoXS have been extended to the areas of structured polymer assemblies, organic electronics, functional nano-composites, liquid crystals, as well as bio/bio-hybrid materials. Recent development of customized instrumentation, multimodal characterization methods, as well as complementary theory and modeling for the extraction of the chemical distribution and spatial arrangement at multiple length scales in the application of soft materials will be discussed.



Presenting Author

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

P80

Latent X-ray and AFM Metrology of EUV Photoresists

Luke Long, Isvar Cordova, Paul Ashby, Andrew Neureuther, and Patrick Naulleau

CXRO, LBL

In response to the need for improved photoresist materials for future EUV nodes, a number of novel materials are being developed to meet the stringent demands of tomorrow's IC manufacturing. However, photoresist design and synthesis still suffer from a lack of precise knowledge about the transfer of pattern information from mask to wafer, particularly at the nanometer scale. One such area that can be measured is the physical and chemical image formed in the photoresist by exposure even prior to dissolution processes. In particular, it is unclear whether photoresist stochastics are due solely to photon and chemical shot noise effects, or whether process variables including bake, underlayer, and development conditions can strongly influence pattern fidelity. Latent image metrology offers an intermediate probe help uncover the complicated interplay of these process parameters. To that end, we present our progress on latent image metrology using atomic force microscopy (AFM) and resonant soft X-ray scattering (RSoXS), focusing on a metal-containing EUV resist as a case study.

Presenting Author

Luke is a graduate student at the University of California at Berkeley, where he is advised by Dr. Patrick Naulleau and Professor Andrew Neureuther. His research focuses on photoresist for the EUV regime, with an emphasis on understanding resist patterning and associated stochastic effects through modeling and measurement. Luke has received recognition for his research accomplishments, most recently in the form of the DOE SCGSR Fellowship and Nick Cobb Memorial Scholarship.

P83

First-Principles Electronic Structure Approaches for EUV Material Systems (Invited)

David Prendergast

LBL (Molecular Foundry)

Presenting Author

David Prendergast is the interim director of the Molecular Foundry, a Department of Energy Nanoscale Science Research Center at Lawrence Berkeley National Laboratory. He is also a Senior Staff Scientist. David received his Ph.D. in physics from University College Cork in Ireland in 2002 and joined the Foundry as a staff scientist in 2007. In his time at the Foundry, he has developed a remarkably broad multidisciplinary research program, involving x-ray science at the Advanced Light Source, and spanning chemical and materials sciences. David's research combines first-principles electronic structure theory and molecular dynamics simulations to study energy relevant processes in complex materials systems at the nanoscale, especially at interfaces, often through direct simulation and interpretation of X-ray spectroscopy experiments.

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