Workshop Abstracts

EUV Litho, Inc.

Organized By:

Vivek Bakshi (EUV Litho, Inc), Chair

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2023 EUVL Workshop Keynote Presentation (Tentative) (Keynote)

Jan van Schoot

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Presenting Author

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

P2

Mask-3D Effects in EUV Lithography and Their Impact on Resolution Enhancements (Keynote)

Andreas Erdmann

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The thick absorber, the reflective multilayer and the off-axis illumination of the mask introduce significant mask-3D effects in EUV lithography. These effects include asymmetric shadowing, pitch dependent shift of the best focus position and image blur, which is caused by the superposition of images resulting from different parts of the illuminator. Various modeling approaches are introduced to explore and understand the peculiarities of image formation and absorber material selection at the resolution limits of EUV lithography.

Low-n absorbers were originally proposed to create attenuated phase shift masks (PSMs) for EUV. Double diffraction of the light by the absorber and the guiding of EUV light through the openings in the absorber layer make the imaging characteristic of such low-n absorbers different from traditional attenuated PSM for DUV lithography. The coupling of light with waveguide modes in the openings of the EUV absorber increases the dependency of the light diffraction on the direction of the incident light. This has strong impact on the shape of the optimum illumination and on source mask optimization (SMO) strategies. Dedicated dual monopole exposure strategies offer interesting options to mitigate image blur and best focus shifts. Multiobjective optimization techniques are employed to explore the high dimensional solution space of SMO and to identify the best imaging options for low k_1 high NA EUV lithography.

Presenting Author

Andreas Erdmann is the head of the Fraunhofer IISB Computational Lithography and Optics Group and teaches as "Privatdozent" at the University of Erlangen. He has more than 25 years of experience in optical and EUV lithography. He chaired SPIE conferences on optical microlithography and optical design and is an organizer of the International Fraunhofer Lithography Simulation Workshop. He contributed to the development of several advanced lithography simulators including the development and research lithography simulator Dr. LiTHO. He is a fellow of SPIE.

P11

Masks for Optimized Imaging with High-NA EUV Lithography (Invited)

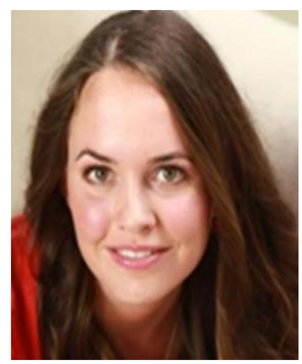
M.-Claire van Lare, Eelco van Setten, Jo Finders

ASML Netherlands B.V. (Netherlands)

With the smaller pitches enabled by high-NA EUV lithography optimizing the mask on several aspects is crucial to meet the tightening EPE requirements. We'll present on a potential scenario for a high-NA mask roadmap, which shows our view on having improved EXE imaging by optimizing the mask absorber, cap and multilayer. We'll show, using NXE experimental data, that low-n absorbers can significantly reduce mask 3D effects leading to improved contrast[1], while at the same time reducing exposure dose. For high-NA EUV lithography, due to the anamorphic design of the scanner, vertical features on the mask are substantially smaller than their horizontal counterparts. For vertical features beyond pitch 26 nm, we propose to re-optimize the thickness of the low-n mask absorber. Furthermore, we'll comment on the imaging impact of the cap layer and the multilayer.

[1] M. van Lare et al., "Investigation into a prototype EUV attenuated phase-shift mask," Proc. SPIE, p. 11609A, 2021

Presenting Author



Claire van Lare obtained her PhD in nanophotonics/physics in 2014. She started at ASML in 2015 and has worked on various topics such as stochastics/resist, EUV imaging/diffraction, and process modeling. She is currently working as a System Engineer EUV Imaging with a strong focus on alternative masks.

P12

Developing Cost-Effective Actinic Solutions for EUV Lithography (Invited)

Dong Gun Lee and Byung Gook Kim

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In order to utilize EUV lithography, various actinic tools are required. However, the high costs of implementing and maintaining these tools, due to the complexity of their EUV sources and optical systems, hinder the development of EUV lithography. Our company, ESOL, has been developing innovative equipment that is significantly more cost-effective compared to existing actinic tools and requires lower maintenance costs. One example is our EUV review system(SREM[1,2]), which employs an HHG source and a diffractive optical system called a Zone plate. We continue to advance these innovative technologies and would like to introduce some notable progress in this area.

[1] D. G. Lee, "Actinic Tools using Coherent EUV Source for High Volume Manufacturing," EUVL Workshop (2020). [2] D. G. Lee and Byung Gook Kim, "Development of advanced blank defect avoidance technique using actinic review system" EUVL Workshop (2021).

Presenting Author

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

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Metal Silicide EUV Pellicle and the Effect of Wrinkles on Mask-3D Effects (Invited)

Dong Gi Lee,[a,c] Seungchan Moon,[b,c] Jinhyuk Choi, [b,c] Seung Ju Wi [a,c] and Jinho Ahn,[a,b,c,*]

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[c]*EUV-IUCC (Industry University Collaboration Center), Hanyang University, Seoul, 04763, Republic of Korea*

Metal silicide has been suggested as a pellicle membrane material for protecting EUV masks from contamination. However, with the upcoming use of high power light sources in High-NA EUV scanners, the energy absorbed by the EUV pellicle will increase, and so we investigated the oxidation characteristics of metal silicide pellicles under heat, as well as the effects of wrinkle formation on the mask's 3D effect.

Our experiments confirmed that metal silicide is susceptible to surface oxidation and requires protection against this. Additionally, we observed that wrinkles in the EUV pellicle can worsen the M3D effects. Through the use of an EUV ptychography microscope, we found that the imbalance in the amplitude and phase of light diffracted from horizontal line and space patterns can increase by 1.56% and 0.045π, respectively, due to pellicle wrinkles. This imbalance results in critical dimension variation, image contrast loss, and pattern shift in the aerial image, and this degradation in imaging performance increases with lower refractive index and higher extinction coefficient.

Presenting Author

Jinho Ahn received his B.S. and M.S. degrees from Seoul National University, and 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 worked as a Director of Nano and Convergence Technology at National Research Foundation of Korea, and the Vice President of Academic Research at Hanyang University. Currently, he is the Director of EUV-IUCC, which is funded by the member companies and partially supported by the Korean government.

P14

High-k Based Near n≈1 EUV Mask for M3D Effects and Focus Control in High-NA Lithography

Dongmin Jeong, Yunsoo Kim, Seung Ho Lee, and Jinho Ahn

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The limited performance of Ta-based mask in high-NA EUV has led to the research of advanced absorber materials for 3nm nodes. However, due to the high transmittance and the significant mask performance changes according to focus shift, necessitates the development of novel absorber to improve productivity. This study investigates high-k EUV mask that enhances mask performance, such as mask 3D effects and focus, while maintaining sufficient imaging performance. The high-k mask was evaluated using PROLITH 2022a simulation with a 5.355 nm EUV wavelength and central obscuration conditions, simulating the high-NA system environment using quadrupole illumination with 20% PFR. Performance comparison was conducted with and Ru mask. Although the high-k mask exhibited slightly lower imaging performance than the Ru mask, met the NILS 2 requirement. Notably, the high-k mask mitigated telecentricity error by more than 48% and reduced the best focus shift by more than 65nm. Additionally, in the CD-DoF was widened by 17%, and in the NILS-DoF was widened by 18% compared to the Ru mask. These results suggest that the high-k mask can mitigate mask performance instability due to focus change and mask 3D effect in high-NA system, making it a promising approach for EUV lithography.

Presenting Author

Dongmin Jeong received his B.S. degree from HUFS in electronic physics, and he is currently studying for a Ph.D. in Materials Science and Engineering at Hanyang University. His research topic is advanced EUV masks for high NA EUV systems.

P15

CNT Pellicles: Recent Optimization and Exposure Results

J. Bekaert, E. Gallagher, M. Y. Timmermans, I. Pollentier, R. Jonckheere, R. Aubert, E. Hendrickx

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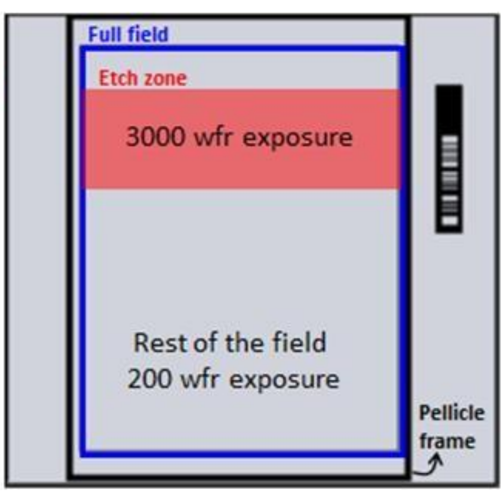
EUV lithography is essential for maintaining semiconductor fabrication roadmaps, and a highly transparent pellicle will enable higher yield while maintaining scanner throughput for volume manufacturing. Current pellicles based on metal silicide are only viable for scanner source powers up to approximately 400 W, due to temperature limitations. For future systems with source power of 600 W and above, novel pellicle types will be required. In 2015, imec proposed a free-standing carbon nanotube (CNT) membrane for the EUV pellicle. With excellent temperature robustness, these are prime candidates for future pellicle application. Carbon Nanotubes (CNTs) can be single- or multi-walled and can vary in diameter and length. The membrane properties can be fundamentally changed to meet the EUV pellicle targets for properties like transmittance, permeability and strength.

In 2021, we reported on the very first full-field CNT pellicle exposures on an EUV scanner, demonstrating EUV transmission up to 98%, with minimal impact of the pellicle on the intrafield uniformity on wafer, and very small flare increase for the uncoated CNT membranes. Because of the Low-DUV reflectivity of CNT pellicles, there is no need to install a spectral purity filter in the scanner.

In this paper, we present experimental data from more recent scanner tests, with focus on the durability of the CNT pellicle in the scanner environment, where the EUV irradiation and hydrogen plasma gradually impact the CNT membrane. Lifetime measurements in off-line tools have been encouraging, but real-world scanner conditions are difficult to replicate. Therefore, obtaining the CNT etch rate on an actual scanner is critical. To this end, we exposed up to 3000 wafers (96 dies at 30 mJ/cm²) from a single pellicle on the ASML NXE:3400B at imec.

Our findings enable us to quantify the impact of longer-term exposure of the CNT pellicles. Fine-tuning the pellicle membrane properties for durability is essential for future HVM EUV lithography at high source power.

a)



b)

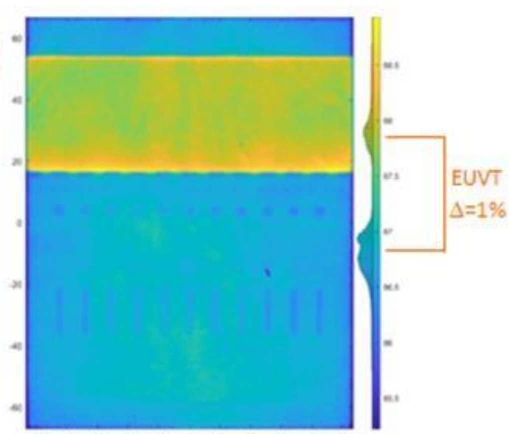


Figure: (a) Schematic of the exposure of the reticle with pellicle (NXE:3400B): The 'etch zone' is exposed with a number of exposure passes that is equivalent to 3000 full-field wafers. The rest of the field is exposed at an equivalent of 200 full-field wafers. (b) EUVT measurement result after the exposure and demounting of the pellicle, showing 1% higher EUVT for the 3000- vs 200-wafer area.

Presenting Author

Joost Bekaert is a senior researcher at imec.

P16

Mask Challenges Towards High-NA EUV Lithography (Invited)

Andreas Frommhold

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We are on the verge of the next big step in lithography technology with the introduction of high-NA EUV. While the change from 0.33 to 0.55NA EUV lithography is not as revolutionary as that from 193 nm to 13.5 nm exposure wavelength, there are still new challenges in many aspects including the mask. I will provide an overview of work carried out in our group to address some of these challenges. This includes the study of mask roughness to further increase our understanding of its contribution to aerial image formation. Mask roughness, or variability in general, manifests as background intensity in the diffraction spectrum, which after frequency filtering by the projection optics is transferred to the wafer. While the contribution is relatively contained for 0.33NA, it is expected to become larger in high-NA.

Another topic of concern is Mask3D effects that will increase at the smaller resolution unlocked by the higher numerical aperture. To mitigate those, novel absorbers and multilayer stacks would be beneficial. Switching to a material with higher absorbance allows for the reduction of absorber height and hence less M3D. Alternatively tuning the refractive index (low-n) to manipulate the phase of the transmitted light in order to improve imaging is another possibility. Finally, to build efficient optics for 0.55NA the printed field size had to be reduced by half. For larger chip designs this requires two half fields to be stitched together. As a consequence, there are new requirements on mask black border control and absorber reflections when the borders of two image fields are overlapped at the stitching region for exposure.

Presenting Author

Andreas Frommhold is a research and development engineer at imec. He received his PhD in electrical engineering on the subject of neural interfaces from the University of Birmingham, United Kingdom. He subsequently worked for 6 years as a research fellow in chemical engineering on photoresists and nanomaterials for semiconductor manufacturing. In 2016 he joined imec, where he is now engaged in various research activities focused on imaging and reticle related aspects of EUV lithography.

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Metrology and Inspection for High-NA EUV Lithography: Challenges and Solutions (Invited)

Roel Gronheid

KLA Corporation, 3001 Haasrode, Belgium

Dimensional scaling of electronic circuits continues to put pressure on the metrology and inspection requirements for enabling R&D as well as process control in manufacturing. Smaller dimensions require improvements in metrology precision and accuracy for parameters such as CD and overlay. On the inspection side smaller and smaller defects become critical for device yield. Identification and classification of such defects with high capture rate and throughput requires continuous attention. In addition, thinner layers are being used for keeping the feature aspect ratio under control, which may negatively impact signal strength for both metrology and inspection. On top of these evolutionary requirements, the introduction of new manufacturing techniques such as high-NA EUV lithography bring additional challenges.

In this contribution, we will discuss a selection of challenges for continued scaling with high-NA EUV lithography as well as innovative solutions to enable continued device miniaturization.

Presenting Author

Roel Gronheid holds a Ph.D. in Photochemistry from Leiden University and had a post-doctoral position at the Catholic University of Leuven afterwards. He joined IMEC in 2003, where he specialized in advanced patterning materials within the lithography department working on the 157nm, 193nm immersion and EUV lithography programs. Roel has initiated and led the directed self-assembly research program. He authored and coauthored over 150 publications and technical conference presentations. In 2016 Roel joined KLA, where he currently works on simulations, metrology and process control for patterning at advanced nodes.

P18

Grazing Incidence Wafer Metrology with REGINE (Invited)

Iacopo Mochi, Tao Shen, Paolo Ansuinelli, Yasin Ekinci
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The REflective Grazing Incidence Nanoscope for EUV (REGINE) is a new end station installed at the XIL beamline of the Swiss Light Source Synchrotron (SLS). REGINE has been developed to combine reflectometry, scatterometry and coherent diffractive imaging techniques for the investigation of wafer samples. REGINE can operate at grazing incidence angles ranging from 6 to 28 degrees and with energies between 86 to 200 eV. In addition, this tool can operate in transmission mode for the study of pellicles and thin films. In this paper we will present the results of the latest experiments we performed with REGINE on membranes and wafer samples, and we will discuss the possibility of coupling the system to a portable soft X-ray source during the upcoming upgrade of the SLS.

Presenting Author

Dr. Iacopo Mochi started working on EUV mask inspection at Lawrence Berkeley Laboratory in the Center for X-Ray optics. He operated the SEMATECH AIT, an EUV microscope for mask review. He later worked on the design and development of SHARP, an advanced EUV mask review tool that is currently operating at the Advanced Light Source in Berkeley. Subsequently, Dr. Mochi worked as an EUV mask R&D engineer at IMEC on the topic of sub-resolution assist features. He is currently a staff scientist at the Swiss Light Source, and he is responsible for the technical development of RESCAN, a lensless actinic system for mask defect inspection.

P19

Probing the Layer and Interlayer Quality of Mo/Si and Ru/Si Multilayers for EUV Mask Blanks (Invited)

Katrina Rook

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Low-pressure ion beam deposition is the process-of-record for the deposition of Mo/Si multilayers for EUV mask blanks. The method is readily extendible to new multilayers for high-NA or hyper-NA, such as Ru/Si or Ru-based alloys. Interfacial quality is widely viewed to impact the EUV performance of the multilayer mirrors. We review recent measurements of the interlayer mixing and particularly the impact of process parameters such as process pressure and ion energy. Lower energy was demonstrated to provide thinner interlayers but led to a reduction in deposition rate and impractical throughput levels. We demonstrate the capability to recover lowenergy deposition rates by at least a factor of 5x via recent technology improvements.

Besides intermixing, there is increasing awareness that other multilayer qualities can impact EUV performance. We present a detailed study, by dark-field TEM, of interfacial roughness at each interface and throughout the multilayer stack. In direct opposition to intermixing, roughness is improved at high ion energy and low pressure. Similarly, film purity is typically expected to improve with ion energy. We preview preliminary measurement of impurity levels in the Mo and Si layers, from secondary ion mass spectrometry and Rutherford Back-Scattering. Simulations are used to predict the impact on EUV reflectivity of interfacial roughness and a variety of potential impurity species.

Presenting Author

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

P20

Investigating the Impact of Multi-Emission Layers on the Emissivity of EUV Pellicles

Young Woo Kang, Seong Ju Wi, Ha Neul Kim, Won Jin Kim, Jungyeon Kim and Jinho Ahn

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EUV pellicle generally have a multilayer structure to simultaneously satisfy the EUV pellicle requirements. However, the impact of interaction between each layer in multilayer structure on the emissivity of EUV pellicles has not yet been reported. In this study, we investigated the influence of multi-emission layers on the total emissivity of EUV pellicle.
We fabricated single-emission layer ($MoSi_2/SiN_x$) and multi-emission layer ($MoSi_2/Si/MoSi_2/Si/MoSi_2/SiN_x$) pellicle with fixed layer thickness of 7 nm $MoSi_2$ and 6 nm silicon. In addition, single $MoSi_2$ pellicle with the same EUV transmittance as the multi-emission layer was fabricated. The emissivity of EUV pellicle was evaluated using a heat load tester emulating EUV scanner environment.

As a result, single $MoSi_2$ pellicle had higher emissivity of 0.25 compared to the multi-emission layer pellicle which demonstrated an emissivity of 0.16. Furthermore, by comparing the emissivity of single-emission layer and multiemission layer, it was confirmed that the increase in the number of layers did not result in a proportional increase in emissivity. Based on these results, we inferred that the low emissivity observed in the multi-emission layer could be attributed to reabsorption of emissions from each layer, leading to an effective decrease in emissivity.

Presenting Author

Young Woo Kang received his B.S. degree from Hanyang University in materials science and engineering, and he is currently studying for a Ph.D. in Materials Science and Engineering at Hanyang University. His research focuses on EUV pellicle fabrication and simulation

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P21

High-NA EUV Optics: Preparing the Next Major Lithography Step (Invited)

Alexandre Lopes, Paul Graeupner, Peter Kuerz

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73447 Oberkochen, Germany

In recent years the promise of EUV lithography became a high-volumemanufacturing reality. With already more than 160 EUV scanners in the field worldwide, this technology has now a solid presence in the market and is currently the main enabler for the latest generations of chips.

To enable the future generations of chips, with even smaller features, ZEISS and ASML are working on the next generation of EUV tools, featuring an increase in the numerical aperture (NA), from the current 0.33 to 0.55. The optical system consists of a highly flexible illumination system and 0.55 NA projection optics, enabling sub-8nm half-pitch single-exposure resolution.

In this presentation we give an overview of the system design of the 0.55 NA optical column and report on the status of the mirror surface polishing, coating, metrology, mirror handling and integration as well as shipment.

Presenting Author

In 2015, Alexandre Lopes received his PhD in Physics at the University of Freiburg, Germany. From 2015 to 2019, he held the positions of R&D Engineer and Team Leader of several DUV and EUV projects at Carl Zeiss SMT. Since 2019, Alexandre has maintained his role as Key Functional Systems Engineer in the ZEISS High-NA program.

Trends in E-Beam Metrology and Inspection (Invited)

Gian Francesco Lorusso
imec, Kapeldreef 75, 3001 Leuven, Belgium

CD SEM technology has changed. For many years, CD SEM metrology has been quite conservative. However, around 2017, we began to observe a sort of restlessness in the field, a trend that was consistently confirmed during the following years. It was surely driven by the daunting specification requirements for advanced metrology nodes, but not only. In fact, we observed a systematic attempt to expand the application space in which the CD SEM had operated, tackling issues ranging from metrology of 3D structures, to edge placement error, voltage contrast, e-beam inspection, and more.

The expansion of the application space has forced CD SEM to evolve in something different: a more flexible and powerful e-beam tool focusing not only on stability and repeatability, but on a range of novel use cases. To implement these new applications, it became necessary to expand the range of various specifications. We observed changes in landing energy, beam current, resolution, as well as algorithms. The detection processes changed too, and higher current and better detection efficiency opened the door to a variety of back-scattered electron applications. Artificial intelligence is becoming critical not only in terms of speed of analysis, but most importantly in terms of quality of the results. Multibeam tools have the potential to become a central technology element in the high-NA EUVL environment, where resolution and throughput for inspection must go hand-inhand.

Presenting Author

Gian F. Lorusso received his PhD in solid state physics from the University of Bari, Italy, in 1992. He has been working on topics related to the semiconductor industry such as metrology tool development, lithography, material analysis and more. His domains of expertise include lithography, metrology, microscopy, and spectrometry. After working at the École Polytechnique Fédérale de Lausanne (Switzerland), the Center for X-ray Lithography (Wisconsin), the Center for X-ray Optics at Lawrence Berkeley National Laboratories (California), and KLA-Tencor (California), he has joined IMEC (Belgium) in 2006. His work has produced more than 230 papers and 17 patents, and was awarded with both the Vladimir Ukraintsev and Diana Nyyssonen awards. He is working on Extreme Ultraviolet Lithography and Metrology, fields in which he started in the early nineties.

P23

Transparent Conductive Backside Coatings for EUV Mask Tuning (Invited)

Klara Stallhofer[1], Philipp Naujok[1], Torsten Feigl[1], Chen Klein[2], Alastair Cunningham[2], Valerio Pruneri[2]

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[2]ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, 08860 Castelldefels (Barcelona), Spain.

Optimization and tuning of photomasks in the lithography process can contribute significantly to reducing process defects on the wafer. In an approach to alter reflective EUV masks in a precise way, reflectivity of the multilayer is to be modified with the help of an ultrashort pulsed laser directed through the mask backside. However, transmission of current chromium nitride mask backside coatings is low at the intended writing wavelength of the laser (1064 nm).

While aiming at an increased transmission at this wavelength, additional boundary conditions need to be fulfilled. The mask backside coating needs to be conductive and mechanically durable to allow electrostatic chucking of the mask, and it has to show a high optical density at the inspection wavelength of 470 nm.
By depositing and characterizing a range of chromium nitride, chromium boride and chromium carbide thin films and combining these with silicon, we identified a promising coating design with increased transmission in the near infrared.

Presenting Author

Klara Stallhofer is working on development and production of EUV coatings as a project lead at optiX fab.
She obtained her PhD at TU Munich, focusing on ultrafast laser spectroscopy, after studying for a Bachelor's and Master's degree in physics.

P24

Optical Materials Constants in the EUV and Their Impact on Scatterometry Measurements

Richard Ciesielski

Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12, 10587 Berlin, Germany

The last years have seen an increased demand for high-accuracy, at-wavelength metrology in the EUV and soft X-ray spectral range. The German national metrology institute, the Physikalisch-Technische Bundesanstalt (PTB), has a long standing expertise in soft X-ray radiometry and scatterometry using synchrotron radiation for metrology applications. We here present measurements and updates of the optical constants of different pure materials and alloys, relevant for EUV optics [1]. Synchrotron-based reflectometry measurements of thin film samples and rigorous mathematical modelling of the retrieved data allows to obtain the optical constants of these materials at wavelengths around 13.5nm.

EUV and soft X-ray scattering data of periodic nanostructures contains information about the geometry of the scatterer on the nanoscale. Reconstructing shape and material distribution from data in k-space is an inverse problem with a large number of unknowns that crucially depends on detailed modelling of the lightmatter interaction with the samples. We present measurements of state-of-the art grating samples and discuss their geometrical reconstruction and the impact of good optical constants data on the accuracy of the method.

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

Presenting Author

Richard Ciesielski joined PTB in 2020 working on the determination of optical materials constants, EUV scatterometry, modeling of complex nanostructures and beamline design for synchrotron applications. He graduated in physics at TU Dresden (Germany) in 2012 and obtained his Ph.D. in physical chemistry from LMU Munich (Germany) in 2016, where he worked on femtosecond pulse shaping microscopy, investigating individual nanostructures. In his postdoc period at LMU, he worked on charge carrier dynamics in perovskite solar cells, using transient optical techniques.

P25

EUV Spectrometry as a Versatile Characterization Technique for Thin Film Layer Systems (Invited)

Sascha Brose[1,2], Sophia Schröder[1,2], Sven Glabisch[1,2], Jochen Stollenwerk[1,2,3], and Carlo Holly[1,2,3]

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[2]JARA - Fundamentals of Future Information Technology, Research Centre Jülich, 52425 Jülich, Germany;
[3]Fraunhofer ILT - Institute for Laser Technology, Steinbachstr. 15, 52074 Aachen, Germany

The introduction of EUV lithography for the high-volume manufacturing of integrated circuits led to a growing demand for accurate metrology techniques in various fields connected to the manufacturing process. The realized stand-alone EUV spectrometer utilizes a compact discharge-produced plasma EUV source for illumination of the sample under investigation. A xenon emission spectrum is measured before and after sample interaction by two sequential spectrographs. By comparing both spectra, the reflectance is calculated within the wavelength range and used for a model-based parameter reconstruction of the layer system. The method has been extended to measure the properties of more complex layer systems and additionally allows for critical dimension metrology of periodically structured surfaces. The presented studies set a basis for the development of an industrial EUV spectroscopy tool that can be used for (in-line) process control in advanced lithographic processes for future nodes.

Presenting Author

Dr. Sascha Brose graduated in mechanical engineering in 2008 and received the Ph.D. degree in mechanical engineering in 2019 from RWTH Aachen University. Since 2019, he is group manager of the research group "EUV technology" at the Chair for Technology of Optical Systems (TOS) at the RWTH Aachen University. Since 2009 he is working in the field of extreme ultraviolet (EUV) applications with focus on the conceptual design, realization and operation of EUV tools for high-precision metrology and nanoscale patterning. His research fields include EUV lithography, EUV metrology and material modification by focused EUV radiation. Additionally, he is expert in micro- and nanofabrication processes of optical components especially designed for EUV wavelengths. He has authored and co-authored more than 35 scientific publications mainly in the field of EUV lithography and metrology.

P31

LWR Offset: Identifying Root Causes by Simulation

Luc van Kessel, Bernardo Oyarzun, Joost van Bree, Ruben Maas

ASML, De Run 6501, Veldhoven, The Netherlands

Further dimensional scaling calls for tighter pattern variability requirements for critical layers. Pattern variability, often expressed as line width roughness (LWR), scales inversely with optical contrast. In the previous EUVL workshop [1], we showed experimentally from 0.33NA EUV exposures that there is a component of LWR that does not scale with contrast. We call this contrast-independent part the LWR offset. The total LWR can be significantly improved if the LWR offset is reduced. It is therefore important to understand its root causes so that targeted efforts can be made to reduce it.

Using an in-house stochastic resist model for both chemically-amplified (CAR) and metal-oxide (MOR) resist, we explore variations in the resist's material and processing conditions that affect the LWR offset. We find that resist granularity (finite molecular size and distribution of chemical species), nonlinear effects during post-exposure bake, and stochastic processes during development are responsible for (part of) the offset. These results indicate that improvements in pattern variability can be achieved by tuning the intrinsic roughness of the resist's material independently of the achieved optical contrast, and provide guidance for future resist improvements.

[1] J. van Bree et al., Photoresist Roughness Understanding & LWR Floor, EUVL workshop 2022

Presenting Author

Luc van Kessel received his PhD in physics from TU Delft in 2022, on simulations of electron-matter interaction. He now works at ASML Research in Veldhoven, focusing on stochastic processes in photoresist.

P32

Organic-Inorganic Hybrid EUV Photoresists Derived from Atomic Layer Deposition (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*

High-NA EUV lithography required for continued extreme downscaling of semiconductor devices demands ultrathin photoresists with high EUV patterning performance and etch resistance. In this talk, I will briefly discuss our current efforts on the vapor-phase synthesis of new organic-inorganic hybrid resists based on atomic layer deposition (ALD) techniques and their electron beam and EUV patterning characteristics. Two distinctive approaches are discussed–vapor-phase infiltration (VPI) and molecular ALD (MALD), where the former utilizes an infiltration of gaseous inorganic precursors into existing organic resists and the latter a cyclic layering of organic and inorganic moieties. Featured systems include an indiumoxide-infiltrated PMMA [1] and a MALD hybrid resist comprising trimethylaluminum (TMA) and hydroquinone (HQ) [2,3]. Given the facile implementation and control of resist composition and characteristics, the ALD-based hybrid resist synthesis has a potential for enabling high-performance EUV photoresist systems.

[1] Subramanian et al., *Proc. SPIE* **PC12292**, PC122920L (2022)
[2] D.N. Le et al., *Proc.* ***SPIE*** **12292**, 1229205 (2022)
[3] W.-I. Lee et al., *Proc*. ***SPIE*** **PC12292**, PC122920K (2022)

Presenting Author

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

P33

Gaining Insights Into EUV Radiation Chemistry (Invited)

Patrick Naulleau

CXRO, Lawrence Berkeley National Laboratory, 54 Cyclotron Rd, Berkeley, CA 94720

Presenting Author

Patrick Naulleau is a senior scientist and director at the Center for X-Ray Optics.

P35

EUV Lithography Patterning Targeting Low Dose and High Resolution Using Multi-Trigger Resist (Invited)

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

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[c]*School of Chemical Engineering, University of Birmingham, B15 2TT, UK*

Research into new resists to support next generation high-NA EUV lithography continues. To contend with shot noise, resists require high EUV absorbance to offset the high-NA need for thin films (as depth of focus may be <20nm). New photoresist mechanisms will be required. Irresistible Materials (IM) is developing novel resists based on the multi-trigger concept which features an inherent dose-dependent quenching behaviour. Previously we have described MTR Generation 1 which incorporated non-metal high-opacity moieties a showed measured absorbances of greater than 18 μm^{-1}.

MTR Generation 2 (Gen2) has focused on reaction mechanism efficiency. Here we present the Gen2.1 approach, based on increasing the activation rate of the monomer activation. We can show good lithographic performance for P28 L/S with doses from 20 mJ/cm^2 to 60 mJ/cm^2. P36 and P34 hexagonal pillars with doses from 30 mJ/cm^2 to 80 mJ/cm^2 have also been patterned. 10nm hp lines at p20 have been successfully patterned at BMET. We have also explored two other routes to improve the Z-factor, optimizing the polymerization mechanism (Gen2.2); and improving the selectivity of the quenching mechanism (Gen2.3). Further the advantages gained by each approach are not correlated, and can be combined for additional Zfactor improvements (Gen2.4; Gen2.5).

Presenting Author

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

P36

Disruptive EUV Material Characterization in imec's AttoLab

Kevin Dorney

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The introduction of EUV lithography into high-volume manufacturing in advanced logic foundries in 2019 has ensured the continual scaling of features in modern micro- and nanoeletronics, thus enabling faster, smaller, and more efficient computing architectures. To harness the power of EUV lithography, a concomitant evolution in the design of EUV materials (photoresists, mask materials, etc.) has taken place, resulting in novel material systems that possess non-trivial properties and chemistries. These disruptive materials require disruptive inspection and metrology techniques that can resolve the fundamental interactions and properties that ultimately determine their performance in lithographic processes and functioning devices.

In order to address this materials characterization challenge, imec has recently installed and commissioned the AttoLab, a state-of-the-art ultrafast laser laboratory with cutting-edge spectro-microscopies for EUV and beyond materials. These techniques, largely centered around table-top EUV sources based on high-harmonic generation, serve as an advanced toolbox for interrogating the properties of novel material systems. In this talk, we will introduce imec's AttoLab as well as provide an overview of current and future activities aimed at advanced material characterization via in-situ EUV spectro-microscopies.

Presenting Author

Kevin Dorney is a researcher in AttoLab at imec in Leuven, Belgium. He received B.S. degrees in Biology and Chemistry (2012) as well as an M.S. in Chemistry (2014) from Wright State University (Ohio, USA). In 2019, he earned a Ph.D. in Chemical Physics under the supervision of Profs. Margaret Murnane and Henry Kapteyn in JILA at the University of Colorado Boulder, specializing in the HHG-based generation of structured EUV beams with tailored spin and orbital angular momentum. His current research revolves around the deployment of bright, coherent 13.5 nm EUV light from HHG systems to investigate the ultrafast radiochemistry of the EUV exposure mechanism in photoresists. In addition, he is also investigating the lithographic performance of photoresists and the development of laboratory-based EUV metrology tools for characterizing current and next-gen semiconductor materials.

P37

The development of computational spectroscopies to unravel atomistic mechanisms in EUVL

Michiel J. van Setten

imec, Kapeldreef 75, 3001 Leuven, Belgium

Fully exploiting limits of Extreme Ultra Violet Lithography requires the optimization of EUV optimized photoresist materials. To develop these, a fundamental understanding of the chemical processes during the exposure step is essential. At imec, in particular at the AttoLab, we use several spectroscopies to monitor changes in model resist materials under exposure to gain understanding of the processes. By comparing these changes to spectra calculated from atomistic models we are ultimately able to map back which atomistic processes are taking place during exposure.

There are, however, several difficulties. To be comparable the spectra need to be calculated with an accurate and hence computationally expensive method. Photo resist materials are quite complex, and a direct ‘brute force’ application of the accurate methods is in practice impossible. Another difficulty, also arising from the complexity of the structures, is that the experimental spectra are average, and it is very hard to track exact changes based on a single type of spectrum.
Here we give an overview of our solutions to deal with these computational difficulties for XPS, UPS and infrared spectra. We show examples of the insights that could be obtained by making a multi spectral comparison between measured and calculated data.

Presenting Author

Dr. Michiel J. van Setten got his PhD. in 2008 from the Radboud University Nijmegen after working on metal hydrides for hydrogen storage. After a postdoc at the Kalsruhe Institute of Technology, working the on development of hydrogen storage materials and electronic structure methods for molecules, and a postdoctoral stay at the Universite Catholique de Louvain, working on manybody perturbation theory, pseudo-potential development, and materials informatics he presently works as a principal scientist at imec. Here he works on the use and development of materials informatics and the linking of ab initio methods to metrology for the semiconductor industry.

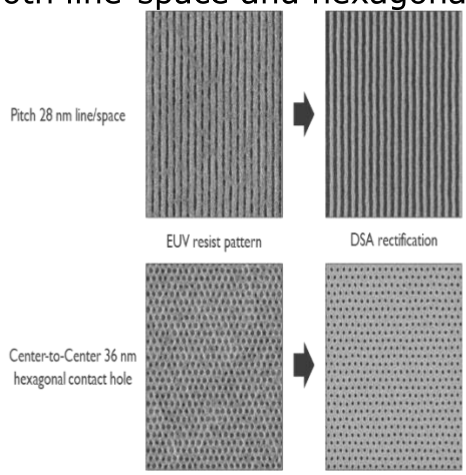
P38

DSA-Assisted EUV Patterning

Hyo Seon Suh, Lander Verstraete, Julie Van Bel, Purnota Hannan Timi, Remi Vallat, Philippe Bezard, Jelle Vandereyken, Matteo Beggiato, Amir-Hossein Tamaddon, Christophe Beral, Waikin Li, Mihir Gupta, Roberto Fallica

imec, Kapeldreef 75, 3001 Leuven, Belgium

To continue the shrinkage of device features as dictated by Moore's law, the industry is now using EUV lithography for the critical layers for scaling. A considerable challenge for printing EUV lithography patterns, however, is coming from stochastics related to photon and chemical shot noise leading to pattern roughness and defects. To mitigate these stochastic issues, directed-self-assembly (DSA) of block copolymers can be used to rectify the EUV resist patterns. Here, we explore the benefits that can be gained by rectification of both line-space and hexagonal contact hole patterns.



Presenting Author

Hyo Seon Suh is a professional DSA (directed self-assembly) engineer with more than ten years of experience in nano-scale patterning with BCP (block copolymer) thin films. He joined imec in 2017 where the main research focus was on the implementation of DSA process at HVM (high volume manufacturing). Currently, he is leading a R&D team focusing on EUV and DSA patterning materials at imec in collaboration with various industry and academia partners.

P39

EUV Lithography Patterning Towards Device Nano-Scaling

Danilo De Simone
imec, Kapeldreef 75, 3001 Leuven, Belgium

Nowadays, the device scaling driven by the Moore's law is continuing by the deployment of the 0.33NA extreme ultraviolet lithography (EUVL) in high volume manufacturing further driven by the need to improve cycle time and cost.

To further simplify and improve EUV patterning reducing cost and enable 2nm technology and below, high NA EUV lithography (0.55NA) is under development.

At the same time, as the nanoscale is pushed further down, the stochastic nature of the patterning process and the thinning down of the films become the major patterning roadblocks. To enable the high NA technology new knobs and faster learning cycles on patterning process development are needed to improve the process window. This presentation will show the latest development on EUV patterning materials and their challenges and provide an insight status of overcoming these obstacles towards the device scaling at nanometric level.

Presenting Author

Danilo De Simone is technical staff member at imec. He has 23 years of experience in semiconductor R&D field and his work has produced over 100 scientific and technical papers in the field of lithographic materials and advanced patterning. Before imec, he has worked for the industry for STMicroelectronics, Numonyx and Micron Technology. He is editorial board member of the JM3 Journal, member of SPIE committee and member of the International Advisory Board of the ICPST conference.

P40

High-NA Era: Interfaces are the New Litho and Etch

Philippe Bezard

IMEC, Kapeldreef 75 3001 LEUVEN

Ultra-thin layers (< 10 nm) have long been used for active components (gate oxide, etc.) and are now becoming increasingly common in sacrificial stacks as well. Consequently, material's behavior is interfacial and not bulk-defined. Interfaces are defined by molecular interactions (surface energy mismatch) and bond lengths (stress and composition). Those then define defectivity, adhesion properties and etch rate. When dealing with ultra-thin layers in lithography or etch, interface engineering thus becomes critical. Plasma and gas processing induce the creation of new interfaces and the modification of existing ones (by adsorption and photon/ ion-induced damages).

In this paper, we will show how tuning interfaces between standard materials can affect defectivity, roughness and etch selectivity, enabling the patterning of ultrathin resists. We will also show how some fundamental differences between atomic layer etching and conventional etch processes in terms of interface formation impacts line roughness.

Presenting Author

Phillippe Bezard has 11 years of experience in plasma-surface interactions (dry-etching, deposition, surface treatment). He has written a PhD thesis on plasma diagnostics and processing of block copolymers for sub-14 nm nodes (dry-etch development, LCDU correction, surface treatments and selective deposition). He holds Several patents and articles on how to prevent dewetting and reduce defectivity for high-xhi DSA. Philippe was the former lead process engineer for plasma-dicing equipment supplier, and now he is currently a R&D dry-etch engineer at IMEC working on High NA patterning and sustainability.

P41

Metal Oxide Resist Formulation and Process Chemistry for High-NA EUV Lithography (Invited)

Sonia Castellanos

Inpria Corporation, 1100 NE Circle Blvd, Corvallis, OR, USA 97330

Metal oxide (MOx) photoresists have demonstrated a unique suitability for the demands of high-NA EUV lithography by successful imaging at the resolution limit of high-NA exposure tools. Properties that make MOx resists the primary candidates for single patterning at sub-20 nm pitches include their excellent EUV absorbance, etch selectivity, and compositional uniformity.

In addition to these critical features, a key requirement of any high-resolution resist is high efficiency chemical processes for transforming absorbed photons into a resolvable latent image. In this work we will discuss the crucial role that the post-exposure bake (PEB) step plays in the enhancement of sensitivity and contrast of MOx photoresists. We will show that the interplay of radiation-induced chemistry and thermally-induced reactions is important for the capture of the projected image with high fidelity. Furthermore, the efficiency of both the EUV- and the PEB-chemistry can be tuned through tailored formulation.

The versatility arising from these adjustable formulations and the controlled impact of the post-exposure processing conditions has enabled continuous improvements to their imaging capabilities in preparation for their implementation in high-NA EUV lithography.

Presenting Author

Sonia Castellanos obtained her PhD in Chemistry from the University of Barcelona (Spain) in 2010, awarded with an Extraordinary Prize. She continued her research on lightresponsive materials at the Humboldt Universitaet zu Berlin (Germany) as a postdoctoral fellow in the frame of an Alexander von Humboldt grant, followed by a second postdoctoral stage at the Delft Technical University (The Netherlands). In 2016 she became a group leader and tenure tracker at the Advanced Research Center for Nanolithography (ARCNL) in Amsterdam, where she investigated the chemistry induced by EUV radiation on metal-oxoclusters. In 2020 she joined Inpria Corporation as a Lead Chemist.

P42

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

Anuja De Silva

LAM

Presenting Author:

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

P43

Challenges for Stochastic EUV Lithography Simulation (Invited)

Ulrich Welling, Lawrence S. Melvin III, Hans-Jürgen Stock

Synopsys GmbH, Karl-Hammerschmidt-Strasse 34/85609 Aschheim/Dornach, Germany

As the demand for smaller structure sizes in lithography continues to increase, it becomes increasingly important to consider details that so far had little impact on the performance of lithographic processes. One such example is the interaction between the underlayer and the photoresist, which must be carefully tuned for optimal resist performance. Lithography simulations can help bridge the gap between process parameters and material properties, but the time and size scales required for lithographic process simulation are far removed from the world of chemistry. As a result, effective models must be used, based on approximations that can break down when the resolution of these effective models is pushed below the nanometer scale.

In this presentation, we will provide an overview on current simulation techniques and discuss how these can be extended to take into account more material properties without creating inaccessible computational costs. We will explore the challenges associated with simulating stochastic processes, such as photon shot noise and the distribution of chemical compounds, and discuss strategies for accurately characterizing these effects in simulations. Additionally, we will outline potential improvements in simulation methodologies and their impact on the development of next-generation lithographic processes.

The overall goal is to provide insight into the challenges associated with stochastic EUV lithography simulations, and discuss potential solutions that can help to bridge the gap between material properties and lithographic process engineering.

Presenting Author

Ulrich is an experienced R&D Engineer at Synopsys, where he focused on developing lithography simulation tools. He has a strong background in material simulation techniques, including atomistic and coarse grained MD/MC methods, as well as fieldbased continuum and surface defined models. Ulrich completed his diploma in chemistry and pursued a Ph.D. and PostDoc affiliation in computer simulations of liquids, liquid crystals, and copolymers for directed self-assembly.

P44

Advanced Resist Patterning Processes for High NA EUV Lithography (Invited)

Seiji Nagahara

Tokyo Electron Limited, Tokyo, Japan

Presenting Author

Seiji Nagahara, Ph.D. is Senior Director / Chief Scientist in Tokyo Electron Ltd (TEL). He now works for marketing and development of the next generation coater and developer equipment and technologies for future lithography 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.

He took Bachelor, Master, and Ph.D. degrees in Engineering at Osaka University, Japan. 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 such as program committee chair of MNC2021.

Fundamental Research of EUV Resist Evaluation at NewSUBARU (Invited)

Takeo Watanabe, Atsunori Nakamoto, Tetsuo Harada, Shinji Yamakawa

University of Hyogo, 3-1-2, Kouto, Kamigori, Akou-gun, Hyogo 678-1205, Japan

The fundamental study of EUV resist using synchrotron is very significant to resolve the way of the RLS trade off, especially to achieve low line width roughness.

According to IRDS 2022 Edition, EUV lithography with high NA of 0.55 is planning to use for high volume manufacturing 2 nm node logic devices around 2025. In high NA of 0.55, the depth of focus on a wafer is calculated to be 45 nm, which is 1/3 of that in NA of 0.33 on EUV lithography. Thus, in the case of high NA, thin resist film should be formed. The resist line width roughness (LWR) become worse as with thickness thinner. Therefore, the origin of the LWR should be clarified from the viewpoint of the aggregation size evaluation. We introduced grazing incidence resonant soft X-ray scattering method to evaluate the aggregation size evaluation of the thickness dependency in the resist film, and it is found its benefit for this evaluation [1].

Other fundamental studies at NewSUBARU synchrotron light facility will be introduced in the presentation.

[1] A. Nakamoto, S. Yamakawa, T. Harada, and T. Watanabe, *J. Photopolym. Sci. Technol.*, **35** (2022) pp. 49 – 54

Presenting Author

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

P46

Advanced Lab-Scale Spectromicroscopies for Characterization and Enhancement of EUV Materials

Kevin M. Dorney[1,*], Nicola N. Kissoon[2], Fabian Holzmeier[1], Esben W. Larsen[1], Dhirendra P. Singh[1], Claudia Fleischmann[1,2], Stefan De Gendt[1,3], Paul A.W. van der Heide[1], John S. Petersen[1]

[1]imec vzw, Kapeldreef 75, Leuven BE, 3000
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[3] Chemistry Department, KU Leuven, Celestijnenlaan 200f, 3001 Leuven, Belgium

The continued miniaturization, speed, and efficiency of modern microelectronic devices has been driven by concomitant advances in photolithography, the fundamental process that creates the tiny patterns making up electronic circuits. The most advanced lithographic processes utilize extreme ultraviolet (EUV) light to print features in photosensitive materials (photoresists) as small as a few 10's of nm. Despite the use of EUV lithography by major chip makers, the action of EUV light on photoresists (and other materials) is largely unknown, which results in variability in the lithographic process and ultimately in device failure and yield loss.

In order to understand the mechanism of EUV exposure, advanced spectroscopies and microscopies are needed that can resolve the action of EUV light on lithographic materials in real time. The AttoLab consortium has focused on the development lab-based spectromicroscopies using accessible EUV sources in order to shed light on these complex processes to provide insights into yet unanswered questions surrounding the lithographic process. These newly developed techniques provide a foundation for enhancing our understanding and ultimately leading to better microelectronic devices across the broad spectrum of ICT components.

Presenting Author

Kevin Dorney is a researcher in AttoLab at imec in Leuven, Belgium. He received B.S. degrees in Biology and Chemistry (2012) as well as an M.S. in Chemistry (2014) from Wright State University (Ohio, USA). In 2019, he earned a Ph.D. in Chemical Physics under the supervision of Profs. Margaret Murnane and Henry Kapteyn in JILA at the University of Colorado Boulder, specializing in the HHG-based generation of structured EUV beams with tailored spin and orbital angular momentum. His current research revolves around the deployment of bright, coherent 13.5 nm EUV light from HHG systems to investigate the ultrafast radiochemistry of the EUV exposure mechanism in photoresists. In addition, he is also investigating the lithographic performance of photoresists and the development of laboratory-based EUV metrology tools for characterizing current and next-gen semiconductor materials.

P47

EUV Reflectometry and Ptychography for the Characterization of Thin Films, Stacks, Photoresists, and In-depth Imaging of Nano-sized structures

Kevin M. Dorney[1,*], Nicola N. Kissoon[2], Fabian Holzmeier[1], Esben W. Larsen[1], Dhirendra P. Singh[1], Claudia Fleischmann[1,2], Stefan De Gendt[1,3], Paul A.W. van der Heide[1], John S. Petersen[1]

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[3] Chemistry Department, KU Leuven, Celestijnenlaan 200f, 3001 Leuven, Belgium

The continued miniaturization, speed, and efficiency of modern microelectronic devices has been driven by concomitant advances in photolithography, the fundamental process that creates the tiny patterns making up electronic circuits. The most advanced lithographic processes utilize extreme ultraviolet (EUV) light to print features in photosensitive materials (photoresists) as small as a few 10's of nm. Despite the use of EUV lithography by major chip makers, the action of EUV light on photoresists (and other materials) is largely unknown, which results in variability in the lithographic process and ultimately in device failure and yield loss.

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Presenting Author

Vitaly Krasnov is a postdoctoral researcher at IMEC/KU Leuven.

P48

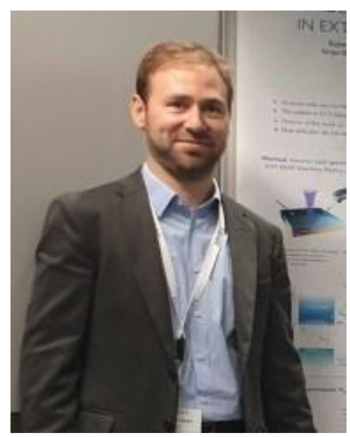
Mean free path of electrons in EUV photoresist in the range 20-450 eV

Roberto Fallica,[a] Nicola Mahne,[b] Thierry Conard,[a] Anja Vanleenhove,[a] and Stefano Nannarone[b]
[a] IMEC, Leuven (Belgium); [b] CNR-IOM, Trieste (Italy)

The mean free path (MFP) of electrons is technologically relevant in many applications of lithography. Lowenergy electrons (≤ 92 eV) generated during EUV lithography can travel considerable distance in photoresist before thermalization which is the ultimate source of resist blur and resolution loss[(1)]. In scanning electron microscopy, secondary and backscattered electrons of energy ≤ 500 eV are emitted from and travel through photoresists films[(2)] while computational metrology attempts to reconstruct the feature size by solving the inverse electron transport equations[(3)]. Similarly, the probing depth of photoemission techniques (UPS/XPS) is strongly variable due to the energy-dependent emission of photoelectrons. All these applications rely on the knowledge of MFP. Models exist[(4)] and predict a "universal MFP curve" for elemental solids[(5)] at high kinetic energy (> 1keV); but these models fail at lower kinetic energy, especially in the solid state.

In this study we measured the MFP of electrons of kinetic energy 20–450 eV in a positive-tone polymer photoresist (PHS+tBMA) with and without PAG (triphenylsulfonium) and quencher (trioctylamine) using energy-dependent photoemission spectroscopy of Si *2p* core levels at CNR-IOM beamline BEAR at Elettra synchrotron (Trieste, Italy)[(6),(7)]. Photoresist damage from the beam was minimized using a one-point-perexposure acquisition strategy. At EUV energy and below, the MFP ranged between 0.85 nm and 2.5 nm, regardless of PAG/quencher content. At energy above EUV, the MFP increased up to 4 ± 2 nm. Results are discussed and compared with previous studies(5),(8),(9).

Presenting Author



Dr. Roberto Fallica received his master's degree in Electronics Engineering from Politecnico di Milano (Italy) in 2007 and completed the PhD school in Nanotechnology from University of Milano-Bicocca in 2012 with a thesis on the characterization of phase-change chalcogenide nanowires for nonvolatile data storage. He was postdoctoral researcher at the Paul Scherrer Institute (Switzerland) working at the dedicated X-ray interference lithography beamline for characterization and patterning of nanoscale photoresist structures. Since 2018, he is staff researcher in the Advanced Patterning department of IMEC (Belgium). His duties include the screening of lithography materials and stacks to develop the technology that will enable future semiconductor devices in BEOL (back-end of line) such as DRAM (storage layer) and logic (metallization). In addition, he collaborates with academia to evaluate fundamental physical properties of EUV photoresists such as electron mean free path and electronic processes by photoemission spectroscopy.

1 J. W. Thackeray, M. Wagner, S. J. Kang, J. Biafore, Journal of Photopolymer Science and Technology, vol. 23, no. 5, pp. 631–637, 2010.
2 M. T. Postek and A. E. Vladár, Proc. SPIE 9927, 99270G (15 September 2016).
3 C. A. Mack and B. D. Bunday, Metrology, Inspection, and Process Control for Microlithography XXIX, 2015, vol. 9424, pp. 117–139.
4 H. Shinotsuka, S. Tanuma, C. J. Powell, D. R. Penn, Surf. Interface Anal., vol. 47, no. 9, pp. 871–888, Sep. 2015. 5 M. P. Seah and W. A. Dench, Surf. Interface Anal., vol. 1, no. 1, pp. 2–11, Feb. 1979.
6 S. Nannarone, F. Borgatti, A. DeLuisa, B. P. Doyle, G. C. Gazzadi, A. Giglia, P. Finetti, N. Mahne, L. Pasquali, M. Pedio, G. Selvaggi, G. Naletto, M. G. Pelizzo, and G. Tondello, AIP Conference Proceedings 705(1), 450 (2004). 7 https://www.elettra.trieste.it/elettra-beamlines/bear.html
8 Y. Ozawa, Y. Nakayama, S. Machida, H. Kinjo, and H. Ishii, Journal of Electron Spectroscopy and Related Phenomena, vol. 197, pp. 17–21, Dec. 2014. 9 H. T. NguyenTruong, Appl. Phys. Lett., vol. 108, no. 17, p. 172901, Apr. 2016.

CHiPPS EFRC at ALS: EUV Photoresist Fundamentals and Soft X-ray Metrology

Cheng Wang

Lawrence Berkeley National Lab, Berkeley, CA

The Center for High Precision Patterning Science (CHiPPS) aims to revolutionize patterning science through a comprehensive approach, focusing on the fundamental interactions of light and matter, and the development of co-designed materials and processes. Our scientific goals are, comprehensively understand phenomena involved in high-precision patterning using EUV photons; create multifunctional radiation-sensitive materials to surpass current photoresist limitations; develop bottom-up hierarchical materials and processes to improve pattern quality and scalability; and establish a test-bed platform to validate the integration of co-designed materials and processes.

In this initiative, multimodal characterization techniques and advanced metrology are being developed to investigate radiation-driven reactions and stochastic phenomena. The focus includes the study of buried chemical profiles, line edge/width roughness, EUV exposure effects, and interfacial chemistry in area selective deposition and etching processes. Recent findings using resonant soft xray scattering (RSoXS) combined with near-edge x-ray absorption fine structure (NEXAFS) demonstrate the unique capability to extract critical information from thin interfacial regions for both top-down and bottom-up patterning approaches. The development of in-situ capabilities and experimental configurations with transmission and grazing incidence geometry contributes to a deeper understanding of each stage in the patterning process.

Presenting Author

Dr. Cheng Wang is a Physicist Staff Scientist at the Advanced Light Source, Lawrence Berkeley National Lab. He is currently a PI and thrust lead for multimodal characterization at the CHiPPS EFRC. He obtained his bachelor's 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

P50

Near-field Infrared Nanoscopic Study of EUV- and ebeam-exposed Hydrogen Silsesquioxane Photoresist

Jiho Kim[1], Jin-Kyun Lee[3], Boknam Chae[1], Jinho Ahn[4], Sangsul Lee[1 2]

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[4]*Division of Materials Sceince and Engineering, Hanyang University, Seoul 04763, South Korea*

We present a technique of scattering-type scanning near-field optical microscopy (s-SNOM) and nanoscale Fourier transform infrared spectroscopy (nano-FTIR) based on scanning probe microscopy (SPM) as a nanoscale-resolution chemical investigation technique of hydrogen silsesquioxane (HSQ) films. Chemical investigations were conducted in the nanometer regime by highly concentrated near-field infrared (IR) on the sharp apex of the metal-coated atomic force microscopy (AFM) tip. When s-SNOM was applied along with Fourier transform infrared (FTIR) spectroscopy to characterize the extreme UV (EUV)- and electronbeam (e-beam)-exposed hydrogen silsesquioxane (HSQ) films, latent pattern images of half-pitch (HP) 100, 200, 300, and 500 nm could be successfully visualized prior to pattern development in the chemical solutions. In addition, nanoFTIR shows position-dependent IR spectra with AFM resolution, which support the latent pattern images. The chemical analysis capabilities provided by s-SNOM and nano-FTIR provide new analytical opportunities that are not possible with traditional e-beam-based photoresist measurement, thus allowing information to be obtained without interference from non-photoreaction processes such as wet development.

This work was supported by National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF-2022M3H4A3088069), and Samsung Research Funding & Incubation Center of Samsung Electronics under Project Number (SRFC-TA1703-051).

[1] J. Kim, J.-K. Lee, B. Chae, J. Ahn, S. Lee, Nano Convergence 9, 53 (2022)

Presenting Author

Jiho Kim graduated from the University of Seoul and received his doctorate degree in Physics in 2019. Since after graduate, he joined the infrared spectroscopy beamline (12D IRS) in Pohang Accelerator Laboratory (PAL) as a postdoctoral researcher. Recently, he joined EUV metrology & inspection group as Staff Scientist and is focusing on the EUV photoresist by using the nano infrared spectroscopy (nano-IR).

P52

Discharge Produced Plasma (DPP) EUV Source Driven By a Solid-State Pulsed-Power System (Invited)

David Reisman, Daniel Arcaro, Wolfram Neff, Michael Roderick, Bob Grzybinski, Scott Moore, and Chris Lee

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

Fred Niell

Nielltronix Inc., Tampa, FL 33609, USA

We will present the development of a new EUV light source using a discharged produced plasma (DPP). The source uses a xenon plasma in a Z-pinch configuration to produce 13.5 nm (±1% BW) radiation. The semiconductor industry uses the source for metrology, mask inspection, and resist development. Based on the successful Energetiq Electrodeless Z-Pinch™ design, the new source uses an innovative transistor-based switching system that overcomes the limitations of traditional magnetically switched systems. With this new configuration both repetition rate and energy per pulse can be significantly increased. Consequently, EUV radiation output, measured in brightness or power, can also be increased. We describe the operating parameters for this system and the resulting electrical and EUV performance.

Presenting Author

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

P53

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

Hakaru Mizoguchi, [3]Kentaro Tomita, [4]Yiming Pan, [5]Atsushi Sunahara, [2,6]Kouichiro Kouge, [7]Katsunobu Nishihara, [1]Daisuke Nakamura, [1]Yukihiro Yamagata, and [1]Masaharu Shiratani

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4. *Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka, 816-8580, Japan*
5. *Center for Materials Under eXtreme Environment (CMUXE), School of Nuclear Engineering, Purdue University, 500 Central Drive, West Lafayette, IN 47907, United States of America*
6. *Present address: 24-8-406 Tatsuno-cho, Hiratsuka, Kanagawa, 254-0046, Japan*
7. *Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, 565-0871, Osaka, Japan*

Recently progress of LPP EUV light source is remarkable. Ten years ago, power level is only several 10 W level. At present 250W power level is realized in semiconductor mass production factories[1)] by ASML. On the other hand, pioneer of this Unique technologies including; combination of pulsed CO_2 laser and Sn droplets, dual wavelength pico second laser pulses for shooting and debris mitigation by magnetic field have been applied by Gigaphoton[2)]. They have demonstrated high average power >300W EUV power with CO_2 laser more than 27kW at output power in cooperation with Gigaphoton and Mitsubishi Electric[3)]. In near future more higher power (>800W) EUV source is required to fit High NA (>0.55) lithography of semiconductor industry.

In this paper we will discuss about the Sn plasma dynamics which dominate the EUV emission by using Tomson scattering (TS) measurement[4)] . Recent TS results have revealed whole profiles of electron temperature and ion density in the EUV sources. These results mention that there is still sufficient potential to increase EUV output in the future.

1) Michael Purvis, Igor Fomenkov, Alexander Schafgans, Mike Vargas, Spencer Rich, Yezheng Tao, Slava Rokitski, Melchior Mulder, Erik Buurman, Michael Kats, Jayson Stewart, Andrew LaForge, Chirag Rajyaguru, Georgiy Vaschenko, Alex Ershov, Robert Rafac, Mathew Abraham, David Brandt, Daniel Brown:" Industrialization of a robust EUV source for high-volume manufacturing and power scaling beyond 250W" Proc. SPIE. 10583, Extreme Ultraviolet (EUV) Lithography IX (2018)

2) Yoshifumi Ueno, Hideo Hoshino, Tatsuya Ariga, Taisuke Miura, Masaki Nakano, Hiroshi Komori, Georg Soumagne, Akira Endo, Hakaru Mizoguchi, Akira Sumitani, Koichi Toyoda : 'Laser produced EUV light source development for HVM', Proc. SPIE 6517 (2007) .

3) Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Krzysztof M. Nowak, Yasufumi Kawasuji, Hiroshi Tanaka,

Yukio Watanabe, Tsukasa Hori, Takeshi Kodama, Yutaka Shiraishi, Tatsuya Yanagida, Tsuyoshi Yamada, Taku Yamazaki, Shinji Okazaki, Takashi Saitou.:" Performance of 250W High Power HVM LPP-EUV Source", Proc. SPIE 10143, Extreme Ultraviolet (EUV) Lithography VIII (2017)

4) Kentaro Tomita, Yuta Sato1, Syouichi Tsukiyama, Toshiaki Eguchi, Kiichiro Uchino (Kyushu Univ.) Kouichiro Kouge, Hiroaki Tomuro, Tatsuya Yanagida, Yasunori Wada, Masahito Kunishima, Georg Soumagne, Takeshi Kodama, Hakaru Mizoguchi (Gigaphoton Inc.), Atsushi Sunahara and Katsunobu Nishihara (Osaka Univ.), "Time-resolved two-dimensional profiles of electron density and temperature of laser-produced tin plasmas for extreme-ultraviolet lithography light sources" Scientific Reports [www.nature.com/scientificreports] (2017)

Presenting Author

Dr. Hakaru Mizoguchi is Senior Fellow, Gigaphoton Inc., and Fellow member of The International Society of Optical Engineering (SPIE). He joined CO_2 laser development program in Komatsu for 6 years since 1982. He was guest scientist of MaxPlank Institute Bio-Physikalish-Chemie in Goettingen in Germany from 1988 to 1990. Since 1990 he concentrated on KrF, ArF excimer laser and F2 laser development for lithography application. 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 up to now. He got Sakurai award from OITDA Japan in 2018. He got IAAM Scientist Award in 2020. He is also guest professor of Kyushu university since 2021.

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

EUV Lighting Technique by the Irradiation of C-Beam and its Characteristics

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[1]Department of Information Display, Kyung Hee University, Dongdaemun-Gu, Seoul, 02447, The Republic of Korea.

Extreme ultraviolet (EUV) sources are the future of semiconductors photolithography and they have been in the future for the long time. EUV wavelength (λ) 13.5 nm was purposed several years ago, and after enormous academic and academic developments, is taking its final steps to enter in high-volume manufacturing. We demonstrate the novel method of the EUV generation by the irradiation of cold cathode electron beam (C- beam). The uniform field emission electron beam of vertically align CNT emitters are directly irradiated to the anode target (Sn) to generate the EUV intensity. The EUV intensity is increased by the optimization of the C-beam structure, anode voltage, anode current, and the angle of the incidence electron beam. This method could be applicable in the semiconductor industry with the high-power efficiency by using the multi-source C-beam.

Reference:

[1] S.T. Yoo, K.C Park, Enhanced extreme ultraviolet lighting using carbon nanotube-based cold cathode electron beam irradiation, Jpn. J. Appl. Phys. (2023).

[2] D. De Simone, Y. Vesters, G. Vandenberghe, Photoresists in extreme ultraviolet lithography (EUVL), Adv. Opt. Technol. 6 (2017) 163-172.

Presenting Author

Bishwa Chandra Adhikari is working as a Research Professor at the Department of Information Display, Kyung Hee University, Seoul, The Republic of Kora since August 2021. Now, He is working in the field of EUV lightning by the C-beam irradiation technique.

P55

High-brightness EUV Source for Inspection and Exposure Applications (Invited)

Yusuke Teramoto[1], Kazuya Aoki[2], Akihisa Nagano[2], Noritaka Ashizawa[2], Takahiro Shirai[2], Shunichi Morimoto[2], Hidenori Watanabe[2], Yoshihiko Sato[2]

[1] *Ushio Germany GmbH, Steinbachstrasse 15, 52074 Aachen, GERMANY*
[2] *Ushio Inc., 1-90 Komakado, Gotemba 412-0038, JAPAN*

Ushio's LDP source (laser-assisted discharge-produced plasma source) is a discharge-driven EUV source using liquid-tin-covered rotating electrodes with an integrated debris filter. It is capable of an operation of a few kHz up to 10 kHz providing brightness of up to 200 $W/mm^2/sr$ or power up to 300 W/2πsr. It is used for sample exposure and mask inspection applications. Results of the development work were deployed to the field sources to improve the performance, reliability and availability. Ushio is also working on a compact EUV source for the applications that does not require high power but very high frequency and high intensity. The compact EUV source under development is capable of providing a focused debris-free EUV beam in the application chamber.

Presenting Author

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

2023 EUVL Supplier Showcase Abstracts

Listed by Abstract numbers

P61

High NA EUV mask blank development with smart factory (I4.0) advanced analytics and AI process control

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High NA EUV lithography requires thinner mask absorbers to reduce the shadowing effect and improve image contrast. Conventional tantalum-based absorbers have low extinction coefficients and cannot provide sufficient mask contrast with reduced thickness. Therefore, new absorber materials with higher extinction coefficients or phase shift properties are needed. There are candidate materials and designs for high NA EUV masks, such as nickelbased alloys, metal oxides, metal nitrides and multilayer phase shifters[1]. New absorber materials can significantly improve image quality and resolution, but also pose new technical challenges for mask production. Mask blank fabrication development options are viewed from a design for manufacturability (DFM) perspective and enabled by advanced analytics and AI process control, as part of smart factory (I4.0) initiatives for advanced manufacturing.

[1] A. Erdmann et al., "Perspectives and tradeoffs of absorber materials for high NA EUV lithography," Journal of Micro/Nanolithography, MEMS, and MOEMS, Vol.19, Issue 4, 041001, Oct. 2020

Presenting Author

Ibrahim Burki works on HOYA LSI's EUV blank technology efforts, leveraging extensive industry experience in semiconductor engineering, manufacturing, technology development and transfer.

Ibrahim's prior work includes technology commercialization and multinational program and project management across the USA, Japan, Germany, Belgium, UAE and Singapore. He has a BS in Physics from the University of North Carolina, Greensboro, an MBA in Technology Commercialization from St. Edward's University, and is currently in the Chief Technology Officer program at The Wharton School.

P62

Industrialization of EUVL and Future Roadmap

TBD

ASML, De Run 6501, Veldhoven, The Netherlands

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Design Approaches for High-Flux High-Harmonic Generation Sources Using Advanced Nonlinear Laser Technologies

Dr. Robert Riedel

Class 5 Photonics GmbH, Luruper Hauptstraße 1, 22547 Hamburg, Germany

High-harmonic generation (HHG) sources are vital in generating high-brilliance laser radiation in the extreme ultraviolet (EUV) to the soft-X-ray range. In this presentation, we give an overview about different design approaches for high-flux HHG sources using our most powerful laser systems based on advanced nonlinear technologies. These technologies include optical-parametric chirped-pulse amplifiers (OPCPA) and multi-pass cells (MPC) in combination with Yb-doped laser systems. This combination allows an immense scalability of average power, and adaptability to optimum HHG driver parameters for increased HHG photon flux.

Laser systems at mid-infrared wavelengths allow the generation of radiation in the water-window spectral range. We demonstrate OPCPA systems designed for 2 and 3 µm wavelength, and average power up to 70 W. Further, we demonstrate laser systems operating in the near-infrared range around 800 nm, targeting the efficient generation of 13.5 nm wavelength. Our results draw a promising roadmap towards next-generation high-flux HHG sources for a wide range of scientific and industrial applications, such as material science and metrology in the semiconductor industry.

Presenting Author

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

P64

An Overview of EUVL Activities at Berkeley Lab

Patrick Naulleau

CXRO-LBL

Presenting Author

Patrick Naulleau is a senior scientist and director at the Center for X-Ray Optics.

P66

Providing Powerful and Stabile Extreme Ultraviolet (EUV) Light to Support the EUV Lithography Metrology Ecosystem

Henry Chou

Energetiq Technology, 205 Lowell St, Wilmington, MA

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

Presenting Author

Henry joined Energetiq in March 2023 as Director of EUV Marketing. He has worked in product management for various capital equipment suppliers in the semiconductor, renewable energies, and consumer electronics industries.

P67

Irradiation System for Testing of EUVL Components – Status of Incorporation

Jochen Vieker

Fraunhofer Institute for Laser Technology - ILT
Steinbachstr. 15, 52074 Aachen, Germany

Fraunhofer ILT has contributed to the development of EUV technology for more than two decades. With a powerful EUV source technology and the know-how on its implementation into optical systems, ILT has been developing a multitude of applications in collaboration with RWTH Aachen University, e.g., EUV laboratoryscale lithography for patterning and resist testing or EUV reflectometry for surface sensitive analysis.

The talk will focus on the incorporation of a new source-collector-module developed for irradiation tests of optical components. The system is based on our proven FS5440 high power EUV source, whose emission is focused on a sample in controllable atmosphere to study EUV induced effects on surfaces and surrounding plasmas. To achieve clean and unbiased experimental conditions, there are no pumping orifices in the vicinity of the focal spot. Using strong vacuum separation and particle mitigation, an operating base pressure $<10^{-7}$ mbar at the irradiation position is expected. The expected performance 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. Design, optical and gas-flow simulations have been presented in previous talks [1]. This talk will discuss the procedures used for acceptance tests as well as first results from testing the effectiveness of the debris mitigation.

[1] Irradiation Systems for accelerated Testing of EUVL Components; 2021 EUV Source Workshop, EUV Litho, inc.; Jochen Vieker

Presenting Author

Jochen Vieker received his Diplom (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 technology and secondary sources based on laser radiation as well as their applications.

P68

Nanoscale Chemical Analysis of EUV Resists

Derek Nowak, Tom Albrecht, Sung Park

Molecular Vista, San Jose, CA

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

Presenting Author

Sung is the CEO of Molecular Vista, which he co-founded with Prof. Kumar Wickramasinghe (UC Irvine, formerly of IBM) in 2011 to provide research and industrial tools for rapid and nanoscale imaging with chemical identification. Sung has over 25 years of experience of industrial R&D, engineering, marketing and sales, and operations. He co-founded Park Scientific Instruments (PSI), which was one of the first commercial companies to develop and sell scanning tunneling microscopes (STM) and atomic force microscopes (AFM). Prior to founding Park Scientific Instruments, he worked as a post-doc at IBM Watson Research Center. Sung earned his Ph.D. in Applied Physics from Stanford University and BA in Physics from Pomona College.

P69

Synchrotron-Radiation Based EUV Metrology at PTB

Michael Kolbe, Christian Laubis, Richard Ciesielski, Victor Soltwisch, Andreas Fischer, Frank Scholze

Physikalisch-Technische Bundesanstalt (PTB), Abbestraße 2-12, 10587 Berlin, Germany

PTB is the German national metrology institute. It supports cooperation partners from industry and science with metrological capabilities and know-how within joint research projects. PTB uses synchrotron radiation in the THz, IR, UV, EUV, VUV, and soft X-ray spectral ranges at the electron storage rings Metrology Light Source (MLS) and BESSY II for basic and applied metrological tasks. For more than 25 years, the EUV-Radiometry group develops and provides metrology services for the characterization of optical components and radiation detectors as well as the measurement of optical material properties in the spectral range from 1 nm to 40 nm. It is worldwide recognized as a well-established partner for EUV metrology. PTB uses its synchrotron radiation laboratories also for lifetime investigations of optical components and radiation detectors. PTB offers services to determine the spectral responsivity of radiation detectors with traceability to a cryogenic radiometer as a primary detector standard in the full spectral range from UV to Xray. The EUV radiometry group uses two measurement stations at the storage rings BESSY II and MLS: an EUV reflectometer which can accommodate large optical components like collector mirrors for EUV plasma sources, and an EUV EllipsoScatterometer for reticle-size samples supporting measurements of reflection and scattering under arbitrary polarization conditions.

The EUV nanometrology group develops methods for the actinic characterization for EUV optical components, e.g., the optical constants of a variety of materials for photomasks have been reconstructed from thin film reflectometry. It also investigates methods for the characterization of nanostructured surfaces, e.g., on wafer, by EUV and soft X-ray scattering and fluorescence.

1. F. Scholze et al.," Metrologia 40(1), S224–S228 (2003).
2. B. Beckhoff et al., physica status solidi b 246(7), 1415–1434 (2009).
3. V. Soltwisch et al., Proc. SPIE 9422, 942213 (2015) [doi: 10.1117/12.2085798].
4. C. Laubis et al., Proc. SPIE 8679, 867921 (2013) [doi: 10.1117/12.2011529]. 5. C. Laubis et al., Proc. SPIE 9776, 977627 (2016) [doi: 10.1117/12.2218902].

Presenting Author

Michael Kolbe received his Ph.D. (focusing on X-ray based analysis) in 2002. Since 2003 he is a scientist at PTB focusing on Metrology with synchrotron radiation. His research activities include X-ray spectrometry, UV/VUV radiometry, and EUV radiometry. Based on these activities, he accumulated expertise in employing analytical techniques in the UV to soft X-ray spectral range. In 2020 he became head of PTB's EUV radiometry group.

P70

Accelerating the Journey to Future Technology Nodes with Veeco's Advanced Technologies in Deposition and Etch

Meng Lee

Veeco

Presenting Author

Meng Lee, Director of Marketing at Veeco Instruments Inc.. He received his Bachelor degree in Electrical and Electronics Engineering from Louisiana State University in 1994 and his Master of Administration (MBA) from California Lutheran University in 2005. He has more than 25 years of experience in capital equipment business, driving strong technology advancement to serve various markets including next generation ion beam deposition and ion beam etch technology for EUV mask.

P71

Patterning control solutions for EUV challenges and readiness towards High NA EUV transition

Ran Alokoken

AMAT

Patterning control solutions for EUV challenges and readiness towards High NA EUV transition While classic, 2D scaling slows down, and as PPACt (Power, Performance, Area-Cost, time to market) becomes a key driver in the industry – new ways to shrink and 3D architectures bring new challenges that call for innovative metrology solutions. Yield-relevant metrology increasingly requires in die, on device information, from across the wafer while maintaining sensitivity.

In this presentation, we will share Applied's view of the EUV most burning patterning challenges, and how a new Patterning Control playbook is leveraging eBeam advantages to complement the traditional metrology methods, and increase yield relevance while making sure High NA challenges are addressed.

Presenting Author

Ran Alkoken is the VeritySEM Product Marketing at Applied Materials, with over 10 years of experience in the Semiconductor industry. Mr. Alkoken is responsible for the definition and development of Applied's CD SEM solutions and roadmap. Started at Intel in 2012 as litho process engineer and joined Applied Materials in 2014 since then has held various R&D positions in application and product management, followed by the current marketing team management role.

Mr. Alkoken holds a BSc. degree in Bio-Technology Engineering from Ben Gurion University and an MSc. in Business Management focusing on strategy and finance from Bar Ilan University, Israel.

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EUV Stochastic Metrology with High Resolution and High Throughput E-Beam System

Abdalmohsen Elmalk

ASML-HMI, 80 W Tasman Dr, San Jose, CA 95134, USA

As nodes continue to shrink and high-NA (HiNA) EUV lithography developments accelerate, the need for accurate, massive critical dimension (CD) and edge placement (EP) metrology at ever smaller scales increases accordingly. ASML's holistic lithography approach relies on e-beam metrology as a crucial component to improve scanner and thus lithography performance and ultimately yield. eP6 is the latest scanning electron microscope (SEM) from ASML-HMI to support the CD+EP application roadmap inside the holistic lithography triangle and introduces three key features. Firstly, with 30% resolution improvement, eP6 can achieve LCDU sensitivity > 90% in the feature size range of 5-20nm. In addition, by beam density increase and noise reduction, CD reproducibility can reach < 0.07nm with comparable throughput to current version. For EP application (Figure 1), combined hardware and software feature optimization, metrology noise can reduce down to 0.25 nm in 8 um field of view, enabling high accuracy EP measurement in the advanced node.

To help customer accelerating process optimization, together with eP6, ASML-HMI provides Process Window Metrology (PWM) application to bring accurate control for High NA EUV process through stochastic aware process windows (SAPW). In figure 2, preliminary thin-resist (< 25nm) study, PWM has demonstrated the capability to differentiate process window difference and decide the best patterning condition for 12.4nm and 13.6nm L/S. Compared to PWM, conventional CD-based process window (CDPW) showed the limitation to distinguish PW on the small features. With new technology from eP6 and PWM, ASML-HMI enables our leading-edge customers to control lithography process more accurately and efficiently.

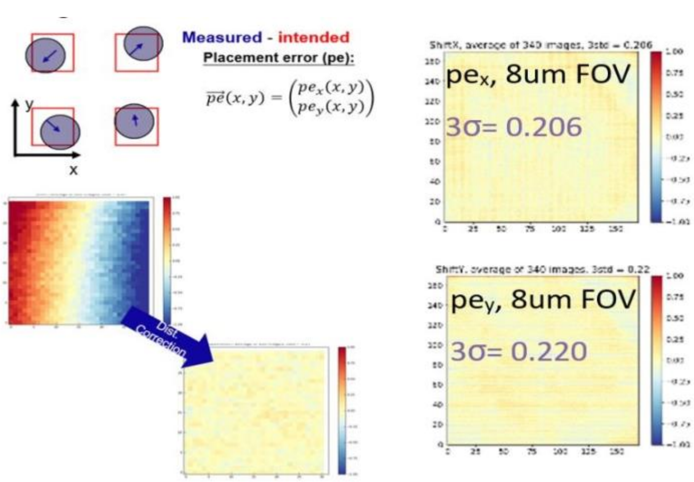

Figure 1

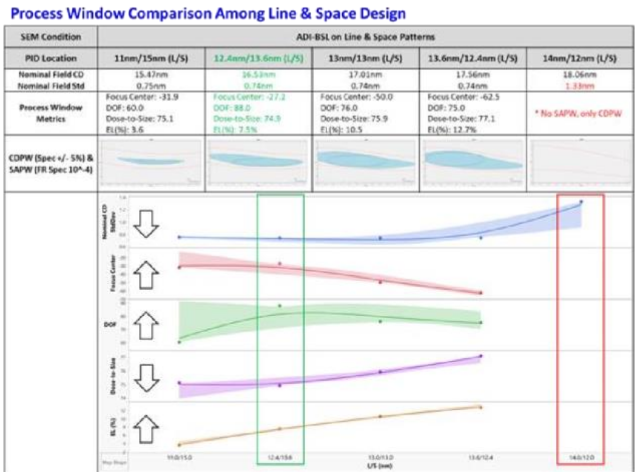

Figure 2

Presenting Author

Abdalmohsen Elmalk is the product performance manager at ASML.

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High Repeatability and Low Shrinkage Solution Using CD-SEM for EUV Resist

Masaki Sugie, Toshimasa Kameda, Shunsuke Mizutani

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EUV resist is prone to damage (shrinkage) caused by electron irradiation during dimensional measurement using electron beam tool, such as CD-SEM. There is a trade-off between measurement accuracy and damage in dimensional measurement of EUV resist patterns. High repeatability and low shrinkage are demanded for metrology. In this study, we propose solutions that can reduce shrinkage and maintain performance of repeatability.

We evaluated shrinkage of EUV resist using 100V low energy electron beam. Shrinkage was reduced with the 100 V electron beam compared to the 300 V electron beam. Meanwhile, repeatability improvement was achieved by multiple proprietary solutions. The CD-SEM with these solutions will be officially announced in the near future under the name "GT2000".

Presenting Author

Masaki Sugie received his master's degree in 2015 from the Department of Informatics at Kogakuin University after working on super-resolution technology for commercial displays. He joined Hitachi High-Tech Corporation in 2015. He was initially engaged in the image processing development of semiconductor inspection equipment and has been working on application development since 2021. He will be assigned to imec in June 2023 as a Hitachi assignee.

P74

Metrology for Scaling Towards 2023

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P75

Modeling Stochastic Effects in EUV Lithography with a Rigorous Physical Simulator

Roel Gronheid

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It is well known that yield-limiting stochastic effects (CDU, LER, bridging/scumming defects) are more significant in EUV lithography than in conventional optical lithography. These effects stem from photon shot noise, chemical shot noise (nonhomogeneous distribution of components within the resist) and secondary electron scattering behavior.

PROLITH™ is a rigorous physical lithography which allows detailed modeling of these stochastic effects, in addition to other important aspects of EUV lithography (Mask shadowing, flare, out-of-band exposure, anamorphic imaging etc.).

Calibrated PROLITH models accurately predict the stochastic behavior of current EUV processes. Taking these models and simulating results for the upcoming high NA EUV exposure systems allows us to make meaningful predictions of process capabilities and entitlements of the process that will run on those tools. We compare results for several different process scenarios.

Presenting Author

Roel Gronheid holds a Ph.D. in Photochemistry from Leiden University and had a post-doctoral position at the Catholic University of Leuven afterwards. He joined IMEC in 2003, where he specialized in advanced patterning materials within the lithography department working on the 157nm, 193nm immersion and EUV lithography programs. Roel has initiated and led the directed self-assembly research program. He authored and co-authored over 150 publications and technical conference presentations. In 2016 Roel joined KLA, where he currently works on simulations, metrology and process control for patterning at advanced nodes.

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Extreme Cleanliness by Dry UHV Processing

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In the semiconductor industry and precision optics, especially for EUVL applications, the demands on component cleanliness are extreme. With conventional cleaning processes, those requirements cannot be met.

Based on desorption in an ultra-high vacuum (UHV) environment, the cleaning systems of the scia Clean series are able to detect and remove even the smallest residual contamination. To optimize the cleaning process further it is possible to add either temperature or plasma treatment. An in-situ mass spectrometer can be used to quantify the cleanliness of the component during cleaning.

Presenting Author

Marcel Demmler graduated in Physical Engineering in 2007. After his graduation, he had a position in the R&D team in a company specified in ion beam and plasma process technologies. In 2011 he started working as a Sales Director in that company. Marcel Demmler joined scia Systems as Sales Director right from the beginning in 2013, coordinating scia Systems' worldwide sales activities.

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Deposition, Etching and Cleaning for EUVL Optics with UHV Processing Equipment

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scia Systems provides precise surface processing equipment based on advanced ion beam and plasma technologies. Especially for EUVL applications we developed equipment for a whole range of processing steps. These are applicable for substrates with sizes up to 1.5 in diameter. We provide systems for Mo/Si multilayer deposition, reactive ion beam etching and high-quality dry-cleaning and qualification. This poster will give an overview about the available technologies.

Presenting Author

Marcel Demmler graduated in Physical Engineering in 2007. After his graduation, he had a position in the R&D team in a company specified in ion beam and plasma process technologies. In 2011 he started working as a Sales Director in that company. Marcel Demmler joined scia Systems as Sales Director right from the beginning in 2013, coordinating scia Systems' worldwide sales activities.

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Performance of a DPP EUV Source driven by a solid-state pulsed-power system

David Reisman

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Presenting Author

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

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An Introduction to EUV Tech

Patrick Naulleau

EUV Tech

Presenting Author

Patrick Naulleau is the CEO of EUV Tech.

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Extreme-ultraviolet metrology at the Synchrotron Ultraviolet Radiation Facility

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The NIST Synchrotron Ultraviolet Radiation Facility offers a full metrology suite for extreme-ultraviolet lithography. These measurements include reflectometry, radiometry, and contamination testing. We have near-term plans to develop EUV ellipsometry and high-power sensors designed to characterize EUVL sources. We'll offer examples of recently developed models to quantitatively describe optics damage processes.

Presenting Author

In 1983, Edward received his B.S. from Clarkson University. He would then go on to receive his M.S. from the same institution in 1986. Edward then attended Howard University, where he received his A.M. and P.H.D. in 1988 and 1994 respectively.

Since 2014, Edwards has been the senior physicist responsible for operations at the Synchrotron Ultraviolet Radiation Facility (SURF III) of the National Institute of Standards and Technology (NIST) at the Gaithersburg, MD campus. The facility supports government as well as industrial partnerships to foster and promote high-tech areas aiding U.S. economic development such as next-generation lithographic technology. In addition, SURF III provides fundamental calibration services for other government agencies such as NASA and NOAA.

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Reflective Optics at Thales SESO: Opportunities for EUV Lithography

Dr. Luca Peverini

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Since more than 50 years Thales SESO (former Société Européenne de Systèmes Optiques) has been a world leading designer and manufacturer of high-end optical components such as telescopes and space observation optics operating over the entire spectral range, from infrared to x-ray wavelengths. Thales SESO has supplied more than 80 Free form optics, which can exceed aspherical departures of 1 mm (slope departures > 30 mrad), with extremely low roughness (<0.1 nm) on Zerodur and Silica material which are suitable for EUV multilayer coatings among others. Thales SESO has now the maturity and the industrial capacity to manage a recurring production of such high level optics, and this activity has already started to serve the semiconductor industry as a credible supplier of optics.

We have pioneered X-ray science conceiving, designing and manufacturing more than 1500 grazing incidence optics [1] requiring extreme performances in terms of shape errors rms (<1 nm) slope errors (<0.1 µrad) and roughness (<1 angstrom), among which more than 400 with lengths > 1 m.

Three ongoing programs are presently calling for unprecedented specifications and a pathway is being drawn to achieve these goals within the next two years and to improve our present means of superpolishing and metrology. These are 1) The EU funded project LEAPS Superflat to demonstrate surfacing with slope errors rms < 50 nrads (1 m length); 2) VIRGO Advanced+ for gravitational waves detection (EGO) calling for shape errors < 0.3 nm (diameter < 200 mm) and 3) a set of EUV collectors and imagers with ellipsoidal shapes and shape errors <2 nm rms. We believe the EUV lithography industry can benefit from these developments for their future equipment.

[1] L. Peverini, H. Guadalupi, T. Michel, S. Perrin, R. Neviere, C. du Jeu, Reflective optics for EUV/X-ray sources at Thales SESO: Possibilities and perspectives, in: Advances in Metrology for X-Ray and EUV Optics IX, vol. 11492, SPIE, International Society for Optics and Photonics, 2020,pp. 92–104, http://dx.doi.org/10.1117/12.2570604.

Presenting Author

Dr. Peverini received his degree and PhD in Physics in 2005 with a thesis work realized at the European Synchrotron Radiation Facility (Grenoble, France). Joined Thales SESO in 2010 where he is responsible for the R&D of X -ray Optics and Product Line Manager of X-ray and EUV Optics for semiconductors, synchrotrons and Free Electron Lasers. He is in charge of the business development of X-ray mirror optics with nano-radian accuracies. He also participate to the R&D activities related to metrology and polishing techniques.

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Intrafield overlay and reproducibility on thin resist towards High NA

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As a result of reduced depth of focus in High NA EUV lithography, resist thickness is expected to decrease below 20nm. The impact of thin resist on various metrology techniques (CD SEM, AFM, PSR, LV SEM and optical defect inspection) has already been studied and presented. [1] The goal in this work is to study the impact of this resist thickness decrease on overlay performance. A set of wafers is prepared with both resists, Chemically Amplified Resist and Metal Organic resist, at various thicknesses. After developing the resist, overlay is measured to the underlying pattern on a YS375 using µDBO targets. As a result of the reduction of the volume of the top grating, because of thinning the resist, a decrease of the signal from the top grating of the target is expected. To address this and to achieve the most accurate overlay measurement, three different types of targets are evaluated to find a solution with a balance between signal from top and bottom gratings. An evaluation is done to select for each type of target, the one with the best performance for the specific stack. Each target and both resists are measured with an optimized profile containing one or more wavelengths and polarizations. The results show good performance for overlay measurements across all resist thicknesses required towards High NA. It is possible to optimize target design and measurement recipe to improve measurement quality.

[1] **"Metrology of Thin Resist for High NA EUVL"**, Published in SPIE Proceedings Vol. 12053, Metrology, Inspection, and Process Control XXXVI, 120530O (26 May 2022)

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