



Workshop Abstracts



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Organized By:

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P1

An Introduction to Quantum Computing and Leading Technologies (Keynote)

Paul B. Welander

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94025*

In this talk I will give an introduction to quantum computing, discuss its history and the present-day quantum ecosystem, and highlight the current state of quantum computing technologies and the challenges they face en route to various application spaces. A leading platform for quantum computing is based on superconducting circuits where nanoscale tunnel junctions play a pivotal role in device operations and performance. I will discuss some specific challenges for this approach to quantum computing and the efforts SLAC is making to address these and advance the state of the art.

Presenting Author

Paul Welander is a staff scientist at SLAC and leads their Quantum Devices Department. His research interests concern materials for quantum devices, from the study of materials-induced decoherence mechanisms in superconducting quantum bits, to the development of materials platforms that enable novel quantum technologies. Paul received his Ph.D. in physics from the University of Illinois at Urbana-Champaign, and holds Bachelor's degrees from both Caltech and Occidental College.



Ecosystem Readiness Towards High NA in IMEC (Keynote)

Kurt Ronse

IMEC, Leuven, Belgium

EUV Lithography using 0.33NA full field scanners, has entered production in 2019 in the biggest foundries, driven by the 7nm logic technology nodes on a limited number of layers. In the meantime, 5nm and 3nm technology have entered production, with more and more EUV layers and also EUV based double patterning. Like for 193nm immersion lithography, EUV multiple patterning becomes increasingly complex and costly, and the cycle time increases. Besides the logic foundries, also the DRAM memory manufacturers announced to start inserting EUV lithography for the same reasons.

In order to reduce cost, complexity and cycle time, High NA EUV lithography is under development. Besides the development of the optics and the scanner, also the complete EUV Eco-system consisting of EUV materials, metrology and EUV masks need to be updated to enable a smooth insertion in High Volume Manufacturing.

As of 2023, imec and ASML will open a high NA EUV Lab, where the first high NA scanner will be installed, together with a track and some metrology systems. In this lab, the ECO-system readiness for high NA EUV will be developed and ultimately demonstrated. In this presentation we will demonstrate the challenges for the high NA ECO-system and give an update of the status of the developments.

Presenting Author

Kurt Ronse, Ph.D. has been working in the field of lithography at imec for over 30 years with responsibilities ranging from lithography researcher, lithography group manager, advanced patterning department director and advanced lithography program director. Currently is leading the Advanced Patterning Program that is focusing primarily on the enablement of High NA EUV lithography ECO system and on the extendibility of EUVL to the next technology nodes for logic and DRAM. Also the feasibility of exploratory patterning techniques like DSA and ASD are being assessed. Prior to joining imec, Ronse received a Ms. and Ph.D. degree in Electrical Engineering from the University of Leuven (Belgium). In 2016, he has been elected Fellow of SPIE for achievements in microlithography and advanced patterning.



High-NA EUV: Getting Closer to Industry Introduction (Keynote)

Jan van Schoot

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At this moment EUV systems equipped with a 0.33 Numerical Aperture (NA) have proven themselves and are successfully applied in high volume manufacturing. At the same time, ASML and ZEISS are in parallel ramping up their activities considerably on an EUV exposure tool with an NA of 0.55. The purpose of this so-called high-NA scanner, targeting an ultimate resolution of 8nm, is to extend Moore's law for at least another decade.

A novel lens design, capable of providing the required Numerical Aperture, has been identified; this so called anamorphic lens will provide 8nm resolution in all orientations. Paired with new, faster stages and more accurate sensors providing the tight focus and overlay control needed it enables future nodes.

In this paper, a short overview of the current state of the 0.33NA technology will be given, after that the advantages of High-NA will be outlined.

Next to this, an update will be given on the status of the developments at ZEISS and ASML. Mirror manufacturing is in full swing, and the first mirrors that have reached their final specification are produced. Integration of the main modules at ASML is ongoing. At the same time the planned Imec-ASML joint lab is being readied to receive the first complete High-NA system. In this lab, customers can start working on High-NA, while the subsequent tools are manufactured and shipped

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



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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

Extending EUV Lithography with High-NA (Keynote)

Steven Carson

Intel, Santa Clara, California

Extreme Ultraviolet lithography 0.33 NA scanners are becoming an established platform for critical layer patterning, and they enable simplified integrated process strategies versus previous 193i technologies. Future node patterning requirements are already forecasting the need for multi-patterning schemes utilizing 0.33NA EUV. The cost and integration complexity of multi-patterning with EUV drives a need for enhanced EUV resolution; that enhancement will be enabled by the 0.55NA "High-NA" scanner. High-NA EUV will introduce new technology challenges in lithographic imaging, but the learnings of 0.33NA provide a solid basis from which to start. A runway for High-NA will be described in this presentation, and the challenges and outlook for its future usage will be considered.

Presenting Author

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



P11

Predictive Stochastic Analysis of Massive Filter-based Electrochemical Reaction Networks

Samuel M. Blau

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94720*

Chemical reaction networks (CRNs) are powerful tools for obtaining mechanistic insight into complex reactive processes. However, they are limited in their applicability where reaction mechanisms are not well understood, and products are unknown. In this talk, I will present new methods of CRN generation and analysis that overcome these limitations. By constructing CRNs using filters rather than templates, we can capture species and reactions that are unintuitive but fundamentally reasonable. The resulting massive CRNs can then be interrogated via stochastic methods, revealing thermodynamically bounded reaction pathways to species of interest, and automatically identifying network products. We apply this methodology to study solid-electrolyte interphase (SEI) formation in Li-ion batteries, generating a CRN with ~86,000,000 reactions. Our methods automatically recover SEI products from the literature and predict previously unknown species. We validate their formation mechanisms using first-principles calculations, discovering novel kinetically accessible molecules. I will conclude the talk by discussing the potential to apply this approach to the electron-driven cascade driving patterning chemistry in EUV lithography.

Presenting Author

Sam Blau grew up in Berkeley, CA and earned his BS in chemistry at Haverford College outside of Philadelphia. He received his PhD in chemical physics from Harvard where he studied exciton dynamics in photosynthesis with Alan Aspuru-Guzik. Sam joined Kristin Persson's group at LBL as a postdoctoral researcher in 2018 where he developed high-throughput workflows and reaction networks for simulating battery electrochemistry. Sam became an independent research scientist at LBL in 2020 and has continued to improve his reaction network infrastructure and leverage machine learning in order to understand and eventually control CO₂ capture, EUV lithography, electrocatalysis, and other complex driven reactive processes.



P12

Nanopatterning with Hierarchical Materials

Ricardo Ruiz

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94720*

Macromolecular self-assembly with hierarchical order has evolved to become an important and valuable tool for bottom-up patterning and fabrication at the nanometer scale. There is no question that the lithographic landscape has been transformed in the past few years with the introduction of extreme ultraviolet (EUV) lithography and the maturity of multiple patterning techniques. At dimensions below 10 nm, emphasis has shifted away from resolution to control of the distributions in stochastic variations highlighting the potential of the tight uniformity achieved by self-assembling hierarchical systems and the exquisite precision afforded by biomolecular assemblies. With features defined at the molecular level and the potential to modular and hierarchical structures, the thermodynamics and kinetic landscape of these self-assembling systems offers a path to unique 2D and 3D architectures. In this talk I will review the current state of bottom-up patterning by hierarchical soft matter, and I will cover current research advances at The Molecular Foundry related to molecular-scale assembly.

Presenting Author

Ricardo Ruiz is a staff scientist at Lawrence Berkeley National Laboratory where he uses Soft Matter Physics to solve nanofabrication challenges at the single-digit nm scale. He received his PhD in Physics from Vanderbilt University in 2003. He was a postdoctoral fellow at Cornell University and later at IBM T.J. Watson. From 2006 to 2019 he held various appointments at Hitachi GST/ HGST/ Western Digital where he contributed to magnetic bit patterned media and non-volatile memories, and he managed a research Group dedicated to block copolymer and nanoparticle lithography. He is a Fellow of the American Physical Society.



P13

Codesign of Ultra-Low-Voltage, Beyond CMOS Microelectronics

R. Ramesh, LBNL& UC, Berkeley, Principal Investigator; co-PIs: L.W. Martin, S. Salahuddin, LBNL & UC Berkeley; S. Griffin, Z. Yao, D. Vasudevan, P. Shafer, J. Shalf, L. Ramakrishnan, LBNL

LBNL, 1 Cyclotron Rd, Berkeley, CA 94720

This proposal aims to develop the co-design framework of atoms-to-architectures to enable sub-100mV switching of non-volatile logic-in-memory, and ultra-efficient digital signal processing for applications such as IoT, sensors and detectors by enabling the materials science, device, and circuit architectures for ultra-low power edge computing. To accomplish this goal, we focus on the manipulation of energy landscapes in ferroic systems which will enable us to tune barriers to switching within prototype devices, create multi-well structures for non-binary logic, and couple charge and spin to build non-volatility. We will harness the unique experimental and computational tools at Lawrence Berkeley National Laboratory (LBNL) to co-design ferroelectrics in transistor logic and multiferroic logic-in-memory devices.

Despite ever-improving computing efficiency, information technology (IT) represents the fastest growing energy consumer and will have significant implications for U.S. energy consumption. This impending challenge threatens the nation's ability to solve important problems across science, technology, national security, and energy. Without improvements in computing efficiency, the explosion of the Internet of Things (IoT) and artificial intelligence (AI) applications will exponentially increase energy consumption. A complete rethinking of how computing is performed today is needed to develop the next-generation of beyond-CMOS microelectronics. Our scientific mission is built on a core guiding principle that a significant opportunity exists for use-inspired basic science to enable highly energy-efficient computing by exploiting correlated phenomena and consequently lowering the operating voltage. Orders of magnitude improvement in energy efficiency are possible by exploiting electronic charge/spin and dipolar order. We will design and manipulate energy barriers to specifically reduce the operating voltage (well below that of today's CMOS technology) to 100 mV and lower, and exploit the non-volatility of these materials in a merged logic in memory fabric to yield 1000x reduction in overall energy consumption

This work will leverage the team's expertise in the synthesis, characterization, and utilization of multiferroic materials and exploit our recent development of an atoms-to-architectures modeling framework that enables us to use supercomputers to evaluate and demonstrate the performance characteristics and feasibility of next generation technology options at multiple levels of detail. The foundation for the critical cross-cutting activities enabled by our co-design framework, Microelectronics

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Codesign Modeling System (MiCoMoS). Within this framework, technologies will be rigorously evaluated for potential benefits on energy and implications on architecture and programming paradigms. The modeling enables us to narrow the design space to the most promising technologies that can then be evaluated experimentally for scale-up issues followed by ramp-up demonstrations. Our proposal leverages and extends existing modeling capabilities within the MATERIALS PROJECT, density-functional-theory codes for modeling of junction physics, the ARTEMIS code for modeling devices, and the PARADISE framework for upscaling from devices to circuits and systems. This multi-scale modeling flow enables us to exploit Exascale HPC capabilities to accelerate development through simulation and modeling using "virtual cycles of learning." We use AI-driven workflow optimizations to integrate our modeling system into a seamless and semi-automated flow to accelerate the evaluation process. By co-designing robust, low-power, low-cost edge algorithms, devices, and supporting ultra-low-power materials systems, DOE will enable scientists to perform large scale experiments in harsh environments (e.g., low temperatures). By embedding AI in this process, we will reduce the time and cost to future new designs. In turn, the team will synthesis candidate materials, fabricate devices, and measure function and metrics to close the co-design loop. There are three critical challenges and associated success metrics: (i) Can we demonstrate robust functioning of ferroelectric and multiferroic layers that switch at voltages < 100 mV in a time scale of < 1 nsec? (ii) Can we use device- and circuit-level modeling and simulations to predict within 10% accuracy the performance of NCFETs and MESO devices? (iii) Can we demonstrate that this diverse team can come together and collaborate across disciplines to achieve a common goal, namely creating the next-generation energy efficient electronics.

Presenting Author

Ramesh pursues key materials physics and technological problems in complex multifunctional oxides. Using conducting oxides, he solved the 30-year enigma of polarization fatigue in ferroelectrics. He pioneered research into manganites coining the term, Colossal Magnetoresistive (CMR) Oxides. His work on multiferroics demonstrated electric field control of ferromagnetism, a critical step towards ultralow power memory and logic elements.

His extensive publications on the synthesis and materials physics of complex oxides are highly cited (over 95,000 citations, H-factor = 148). He is a fellow of APS, AAAS & MRS and an elected member of the U.S. National Academy of Engineering and a Foreign member of the Royal Society of London as well as the Indian National Science Academy. His awards include the Humboldt Senior Scientist Prize, the APS Adler Lectureship and McGroddy New Materials Prize, the TMS Bardeen Prize and the IUPAP Magnetism Prize and Neel Medal. He was recognized as a Thomson-Reuters Citation Laureate in Physics for his work on multiferroics.

He served as the Founding Director of the successful Department of Energy SunShot Initiative in the Obama administration, envisioning



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and coordinating the R&D funding of the U.S. Solar Program and spearheading the reduction in the cost of Solar Energy. He also served as the Deputy Director of Oak Ridge National Laboratory and the Associate Lab Director at LBNL. Most recently, he served on the Biden-Harris Transition Team for Energy.

P14

Probing Morphology and Chemistry in Complex Soft Materials with *in situ* Resonant Soft X-ray Scattering

Cheng Wang

Advanced Light Source, Lawrence Berkeley National Lab

Small angle scattering methodologies have been evolving at fast pace over the past few decades due to the ever-increasing demands for more details on the complex nanostructures of multiphase and multicomponent soft materials like polymer assemblies and biomaterials. Currently, element-specific and contrast variation techniques such as resonant (elastic) soft/tender x-ray scattering, anomalous small angle x-ray scattering, and contrast-matching small angle neutron scattering, or combinations of above are routinely used to extract the chemical composition and spatial arrangement of constituent elements at multiple length scales and examine electronic ordering phenomena. Here we present some recent advances at ALS in selectively characterizing structural architectures of complex soft materials, which often contain multi-components with a wide range of length scales and multiple functionalities, where novel resonant scattering approaches have been demonstrated to decipher a higher level of structural complexity that correlates to functionality. With the advancement of machine learning and artificial intelligence assisted correlative analysis, high-throughput and autonomous experiments would open a new paradigm of material research. Further development of resonant x-ray scattering instrumentation with cross platform sample environments will enable multimodal in-situ/in-operando characterization of the system dynamics with much improved spatial and temporal resolution.

Presenting Author

Dr. Cheng Wang is a Physicist Staff Scientist at the Advanced Light Source, Lawrence Berkeley National Lab. He obtained his bachelor's degree in physics from Jilin University, China in 2002, and received his Ph.D. in physics in North Carolina 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.



P15

Uncovering Local Interactions and Morphology in Soft Materials with Chemically Sensitive X-rays

Gregory Su

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94720*

Developing next-generation soft and hybrid materials for energy applications requires understanding material properties from the molecular to mesoscale. Energy-resolved x-rays provide a route to probe local interactions with elemental sensitivity and nanoscale morphology. We show that *in situ* X-ray absorption spectroscopy probes the key electronic interactions between the open metal sites and adsorbed guest molecules in a nanoporous framework that contains coordinatively unsaturated Cu^I centers and is promising for hydrogen storage and gas separations. Additionally, we show that energy-resolved resonant x-ray scattering reveals detailed aspects of the nanoscale phase separated morphology in ion-conducting polymer membranes used in fuel cells and electrolyzers, providing guidance for design of new membranes with improved conductivity.

Presenting Author

Gregory Su is a staff scientist at the Advanced Light Source and Materials Sciences Division at Lawrence Berkeley National Laboratory. Gregory received his B.S. in Chemical Engineering from UMass Amherst and his PhD in Materials from UC Santa Barbara, where he studied morphology-transport relationships in organic semiconductors for flexible electronics. He was a postdoctoral research fellow at Lawrence Berkeley National Laboratory before starting as a staff scientist in 2020.



P16

Spin textures, Skyrmions for Novel and Energy-efficient Microelectronics

Mi-Young Im

LBNL, 1 Cyclotron Road, CA 94720

The impending end of Moore's law has propelled advanced microelectronics device research to more innovative and disruptive methods. Skyrmion-electronics is one of the classes considered promising for energy-efficient novel microelectronics. Skyrmions are spatially localized quasiparticle-like chiral spin texture. Their nanoscale size, superior stability, dual functions of data storage and transfer, energy efficient operation in CMOS-compatible metallic thin films, as well as their purported efficient coupling to electrical currents, promise skyrmion-electronics for next-generation memory, logic, and neuromorphic/reconfigurable computing applications such as skyrmion racetrack memory and skyrmion-MTJs (Magnetic Tunnel Junctions) [1, 2]. In our works, we addressed several critical scientific issues and provided essential technological information for realizing skyrmion-based microelectronics: efficient creating, deleting skyrmions [3-6], modulating size, density, and stability of skyrmions [5, 7], current-driven transport of skyrmions [3], etc.

In addition, we are developing a novel concept beyond traditional single skyrmions: "Skyrmion Bags" that can hold a variable number of skyrmions in two regions: a core and the perimeter. Rather than using trains of single skyrmions to encode binary bits, each skyrmion bag can encode multiple numbers represented by several bits, leading to massively dense data storage and multi-valued logic computation. Through this work, we are already able to demonstrate fundamental phenomenon of skyrmion bag creation, annihilation, and transport. This demonstrated capability enables us to build a highly dense data storage circuits for efficient on-chip memory scalability. Need for ultra-energy efficient, yet large on-chip memory is highly sought criteria for powerful computing system design. Also, computational primitives based on the interaction of skyrmion bags were implemented, which represents abstract computing logic similar to a look-up/truth table. Combining already demonstrated high-density skyrmion bag memory with these high-density computing primitives paves the way for realizing powerful computing architectures [8].

[1] A. Fert, N. Reyren, V. Cros, Nature Rev. Mat. 2, 17031 (2017).

[2] D. Pan et al., IEEE J. Electron Devices Soc. 7, 529 (2019).

[3] S. Woo et al., Nat. Maters. 15, 501 (2016).

[4] Zidong Wang et al., Nature Electronics 3, 672 (2020).

[5] Anjan Soumyanarayanan et al., Nat. Maters. 16, 898 (2017).

[6] Soong-Geun Je et al., Nano Lett. 21, 3, 1253-1259 (2021).

[7] Soong-Geun Je et al., ACS Nano, 14, 3, 3251 (2020).

[8] D. Vasudevan et al., to be submitted (2022).

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Presenting Author

Dr. Mi-Young Im is a staff scientist at Lawrence Berkeley National Lab. in Berkeley, USA. Dr. Im's expertise is in nano-magnetism, nano-spintronics, and spin (magnetic) dynamics. Dr. Im's research based on direct imaging spin structures/textures utilizing full-field soft X-ray microscopy have tackled a number of fundamental scientific questions about nanoscale spin behaviors and technological problems that are highly relevant to the exploitation of magnetic and spin structures/textures in a wealth of technological applications for energy-efficient advanced memory, logic, and computing devices.



P18

Patterning Potential Landscapes on an Atomically Thin Canvas

Archana Raja

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Semiconducting transition dichalcogenides like MoS₂ are layered van der Waals crystals that can be prepared at the atomically thin limit of a quasi-two-dimensional (2D) material. These 2D materials exhibit extraordinary light-matter coupling and highly tunable electronic properties, which has allowed for the design of devices at the limit of Moore's law. However, by virtue of being a molecule thick, these 2D semiconductors are very sensitive to the local environment. One can leverage this environmental sensitivity to non-invasively modulate the electronic properties of the 2D semiconductors by encapsulating it in tailor-made substrates [1]. In this talk, we will propose to exploit these properties by creating nanoscale patterned environments for transport of charge, energy and information, and discuss opportunities and challenges in their implementation.

[1] Raja et al. "Coulomb engineering of the bandgap and excitons in two-dimensional materials." *Nature Communications* 8,15251 (2017).

Presenting Author

Dr Archana Raja is a Staff Scientist at Lawrence Berkeley National Laboratory. Her research group is based at the Imaging and Manipulation of Nanostructures Facility at the Molecular Foundry, a nanoscale science research center based at Berkeley Lab. She received her PhD in Chemical Physics from Columbia University. After spending a year as a postdoctoral scholar in the Applied Physics department at Stanford University, she joined the Kavli Energy and Nanoscience Institute at UC Berkeley as a Heising-Simons Junior Fellow. Her research focuses on manipulating potential landscapes in nanoscale quantum materials for transport of energy, charge, and information.



P31

Novel Diamond-Like-Carbon Capping Layer for EUV Masks (Invited)

Antonio Checco

*Veeco Instruments, Advanced Deposition and Etch,
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State-of-the-Art EUV mask blanks are based on Mo/Si multilayers, tailored for high reflection at 13.5 nm. The multilayers are capped with a thin ($\sim 3\text{nm}$), protective layer of ruthenium. Ru is the current capping material of choice, despite suffering from mechanical attack during downstream processing and mask cleaning.[1] Furthermore, multilayer reflectivity (EUV-R) is suppressed by $\sim 3\%$ by the presence of the Ru cap layer.

We study experimentally the Ru thickness dependence of EUV-R, and show R_{max} to be deteriorated by at least 1.8%, even for Ru down to 1nm. Optical modeling supports the experimental data, once we account for realistic Ru-Si intermixing and Ru oxidation.[2]

We investigate ultra-thin Diamond-Like-Carbon (DLC) as an alternative capping material for the Mo/Si multilayer, owing to its chemical resistance and low adsorption in the EUV. We find that DLC coatings with thickness in the 2-3nm range degrade EUV-R by only 0.6%, a significant improvement over Ru layers. Moreover, we evaluate the reflectivity characteristics of hybrid DLC/Ru capping layers. Results show no improvement of EUV-R over Ru layer, although hybrid capping layers may exhibit improved chemical resistance.

These experimental findings are well modeled by EUV reflectivity simulations, which include realistic interlayer mixing, and surface oxidation layers.

[1] D. Dattilo, U. Dietze, J.-W. Hsu, Proc. SPIE 9635, Photomask Technology 2015, 96351B (23 October 2015)

[2] A. V. Tikhonravov, M. K. Trubetskov, OptiLayer thin film software // <http://www.optilayer.com>

Presenting Author

Dr. Antonio Checco is Research Scientist with the Advanced Deposition and Etch division of Veeco Instruments. Antonio has 18 years' experience in thin-film deposition and characterization techniques. He received his MS in Physics from the University of Calabria (Cosenza, Italy), and his PhD in Physics from University Pierre and Marie Curie (Paris, France). Since joining Veeco in 2020, he has been engaged in the EUV program, specifically process development for mask-blank multilayer deposition.



P32

EUV Lensless Imaging with Synthetic Pupil Illumination (Invited)

Iacopo Mochi, Hyun-su Kim, Tao Shen, Yasin Ekinci

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Switzerland*

EUV lensless imaging, also known as coherent diffraction imaging (CDI) is an alternative approach to conventional actinic metrology for EUV lithography. The RESCAN microscope was developed at PSI as a synchrotron-based test bed to evaluate the potential of lensless metrology for actinic patterned mask inspection. RESCAN can perform lensless inspection of absorber and phase defects as small as 20 nm on bare and pellicle-protected photomask samples.

Conventional mask inspection and review tools are equipped with flexible illumination systems, however, most lensless imaging applications have a fixed illumination. To overcome this limitation, RESCAN was recently equipped with a Fourier synthesis illuminator which allows users to change the illumination angle of incidence on the photomask.

As the name implies, an essential requirement for CDI is coherent illumination, therefore the illumination must be static, and a different image must be reconstructed for each angle of incidence. We can use multiple images obtained with CDI at different incidence angles, to synthesize a complex illumination pupil. In this work, we will present the commissioning of the new illumination system of the RESCAN microscope, and we will discuss the potential of lensless imaging with pupil synthesis in EUV metrology applications.

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.



P33

An Actinic Review System Consisting Only of Diffractive Optical Elements (Invited)

Dong Gun Lee and Byung Gook Kim

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

The application of EUV lithography to mass production of semiconductors means that EUV mask production technology, one of the materials required for exposure equipment, has been completed. In terms of creating systems using EUV optics, the EUV mask could provide options for new EUV optics systems. The EUV mask can be applied as a diffractive optical element that acts as a condenser for a large area and high NA. And thus, this prior development techniques can be used to create high-performance EUV optical systems.

ESOL has developed an actinic defect review system called SREM [1-2]. In SREM using a Zone plate lens as an imaging optic, applying an EUV mask as a condenser can dramatically improve the system's performance. At this time, the EUV mask is in the form of a reflective zone plate lens. In this presentation, we would like to introduce a new EUV review system being developed at ESOL.

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



Optimization of the Diffraction Phase Effect for EUV Phase Shift Mask (Invited)

Dongmin Jeong^{a,c}, Yunsoo Kim^{a,c}, Minsun Cho^{b,c}, Jinho Ahn^{a,b,c}

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Alternative EUV PSM has the potential to improve mask performance by reducing M3D effects and boosting the optical contrast in high-numerical-aperture systems. However, achieving the ultimate optical contrast limit of the EUV mask is greatly impeded by the diffraction properties of EUV light. In this work, we tried to improve the imaging performance of the EUV PSM further by optimizing the phase delta of EUV diffracted orders. We investigated the effects of phase delta between the 0th and 1st diffracted orders for the low- n ($0.87 \leq n \leq 0.91$) absorber. The RCWA simulation was performed for 0.33-NA 14 nm half-pitch and 0.55-NA 12 nm half-pitch line and space patterns with a leaf dipole off-axis illumination condition. We found that the image split, which means the distance between the aerial image formed from each pole, was reduced by using the optimum phase delta between the 0th and 1st diffracted orders. As a result, the optimum phase deltas were 0.15π and 0.2π for 14nm and 12 nm L/S patterns, respectively. In addition, this result became more evident as the amplitudes were balanced between the 0th and 1st diffracted orders. In conclusion, it is possible to maximize mask imaging performance by phase control for a low- n absorber while the amplitude difference between 0th and 1st diffracted orders was minimized.

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.



P35

Progressing Insights on Low-n Masks for EUV Lithography (Invited)

M.-Claire van Lare, Tasja van Rhee, Mykyta Voronov, Toine van den Boogaard, Jo Finders

ASML Netherlands B.V. (Netherlands)

In EUV lithography optimizing the mask on several aspects can strongly help to meet the tightening EPE requirements for low-k1 imaging. Low-n absorbers have been shown to significantly reduce mask 3D effects leading to improved contrast¹ at the same time, they show substantial dose improvements, by having their optimal contrast at more open mask bias values. We will present on our progressing insights on low-n absorbers. Experimental data on LCDU improvement for dense features will be shown. We will discuss best-focus shifts through pitch for the low-n mask vs its Ta-based counterpart and provide guidelines on printing through-pitch with the low-n mask. Furthermore, we will show our latest experimental data that go beyond dense patterns and address the mask's overall lithographic impact.

[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.



Understanding Line-Edge Roughness in Extreme Ultraviolet Lithography and Fin-Field-Effect-Transistor: Computational Study

Sang-Kon Kim

The Faculty of Liberal Arts, Hongik University, Seoul 04066, Korea

Line-edge roughness (LER) is one of the critical issues that significantly affect the critical dimension (CD) and the device performance because LER does not scale along with the feature size. This study introduces modeling the extreme ultraviolet lithography (EUVL) processes with 5-nm pattern performance using the Monte Carlo method by describing the stochastic fluctuation of the exposure due to the photon shot noise and resist blur. LER impacts on the performance of the fin-field-effect-transistors (FinFETs) are investigated using a compact device method. Electric potential and drain current with the fin-width roughness (FWR), which is based on LER and the line-width roughness (LWR), are fluctuated regularly and quantized as the performance degradation of FinFETs.

Presenting Author

Kim, Ph.D., has been an associate professor at the Faculty of Liberal Arts, Seoul campus, in Hongik University, since 2020. He was a research professor and post-doc at the HRDPI of Bionano Fusion Technology, ERICA campus, in Hanyang University during 2007-2011. Kim was a team leader for Hanwha Corporation / Telecommunication company. During his two years at the Hanwha company, Kim spent time fabrication and packaging the 155 Mbps optical transmitter/receiver modules. During three years, April 1990 ~ January 1993, Kim spent time doing the chip testing software such as the fault simulator at the ASIC division of Samsung Electronics in Korea.

Kim received a bachelor's degree in Physics from Hanyang University, Seoul, Korea, a master's degree from Northeastern University, Boston, MA, United States, and a Ph.D. in Physics from Hanyang University, Korea. Kim has modeled lithography processes for computer simulation and has compared those results to the experimental results. He has the honor of a Best Academic Poster Award at the SPIE Microlithography Symposium Conference (2006) in the USA, the Best Paper Prize at the 7th International Nanotech Symposium & Exhibition in Korea (NANO KOREA, 2009), and Samsung Electronics Co. Paper Award (2013) at the 19th Korean Conference Semiconductors in Korea (2012).



P37

Effect of wrinkles on Pellicle Reflectivity and Local Critical Dimension

Seung Chan Moon, Dong Gi Lee, Young Woong Kim, Jin Hyuk Choi and Jinho Ahn

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

As EUV pellicle is applied as a solution for mask defect mitigation, its EUV reflectance (EUVR) less than 0.04% is required to prevent critical dimension drop (dCD) at the intra-field corner and edge. [1]. In the meantime, the wrinkles on the pellicle can affect the optical properties of pellicle like EUVR.

In this study, we experimentally investigated the change of EUVR induced by the pellicle wrinkles and its effects on mask imaging performance with EUV ptychography microscope, an actinic tool using high harmonic generation source.

As a result, we confirmed not only a local increase of EUVR (higher than 4X) but also randomly changed beam path of the reflected light at the wrinkled area. To confirm the effect of increased EUVR on the mask imaging performance, we reconstructed the aerial images using a ptychographic algorithm after synthesizing the reflected EUV light into a mask diffraction pattern. dCD depends on the relative position of the reflected light from the wrinkle to the 0th or 1st order diffracted light. dCD as large as 6nm was observed.

Therefore, even if the pellicle satisfies the EUVR requirement, we need to tightly control the generation of wrinkles to suppress CD variation during the exposure process.

[1] D. Brouns, "ASML NXE pellicle update", SPIE proc. 11178, 1117806 (2019)

Presenting Author

Seung Chan Moon has been researching actinic inspections for EUV mask and pellicle at Hanyang University, Seoul since 2021, under professor Jinho Ahn. Prior to 2021, he studied material science and engineering at Hanyang University, Seoul.



P42

High Power LPP-EUV Source for Semiconductor HVM; Lithography and Other Application (Invited)

Hakaru Mizoguchi, Senior Fellow of Gigaphoton Inc.

Gigaphoton, 400 Yokokura-shinden Oyama-shi Tochigi, 323-8558, JAPAN

Gigaphoton has developed LPP EUV light source which is the most promising solution as the 13.5nm high power light source for HVM EUVL. Unique and original technologies including: combination of pulsed CO₂ laser and Sn droplets, dual wavelength pico second laser pulses for shooting and debris mitigation by magnetic field have been applied¹⁾. We have demonstrated high average power CO₂ laser more than 25kW at output power in cooperation with Mitsubishi Electric²⁾.

Pilot#1 demonstrated HVM capability; >300W operation data (short-term) and actual collector mirror reflectivity degradation rate is less than 0.15%/Gp³⁾ by using real collector mirror around 125W (at I/F clean) in burst power > 10 Billion pulses operation⁴⁾. Long-term operation over 270W is also successful. Also, we are developing small LPP light source for new application. I will report this new LPP light source at the conference.

[1] Hakaru Mizoguchi, et. al.: "Sub-hundred Watt operation demonstration of HVM LPP-EUV source", Proc. SPIE 9048, (2014)

[2] Yoichi Tanino et.al.: "A Driver CO₂ Laser Using Transverse-flow CO₂ Laser Amplifiers", EUV Symposium 2013, (Oct.6-10.2013, Toyama)

[3] Hakaru Mizoguchi, et al.: " High Power HVM LPP-EUV Source with Long Collector Mirror Lifetime", EUVL Workshop 2017, (Berkeley, 12-15, June, 2017)

[4] Hakaru Mizoguchi et al.: " Challenge of >300W high power LPP-EUV source with long collector mirror lifetime for semiconductor HVM", Proc. SPIE 11323, Extreme Ultraviolet (EUV) Lithography XI (2019) [11323-28]

Presenting Author

He is Senior Fellow of Gigaphoton Inc., Fellow of The International Society of Optical Engineering (SPIE), and member of The Laser Society of Japan and The Japan Society of Applied Physics. He joined CO₂ laser development program in Komatsu for 6 years. After that he was guest scientist of Max-Plank Institute Bio-Physikalish-Chemie in Goettingen in Germany 2 years, from 1988 to 1990. Since 1990 he concentrated on KrF, ArF excimer laser and F₂ laser research and development for lithography application. He was general manager of research division in Komatsu Ltd. until 1999. He got Dr. degree in high power excimer laser field from Kyushu university in 1994. In 2000 Gigaphoton Inc. was founded. He was one of the founders of Gigaphoton Inc. From 2002 to 2010 he organized EUV research group in EUVA program. Now he is promoting EUV light source product development with present position. He got Sakurai award from OITDA Japan in 2018. Also, he got IAAM Scientist Award in Advanced Materials Lecture Series 2020.



P43

Modeling the EQ-10 Discharge Produced Plasma (DPP) EUV Source (Invited)

David Reisman

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

The EQ-10 Electrodeless Z-pinch™ source uses Xenon plasma to produce 13.5 nm ($\pm 1\%$ BW) radiation. The source is used for metrology, mask inspection, and resist development. In this talk we will discuss simulations of the EQ-10 Z-pinch using radiation-MHD codes. Using calculations, we show that the energy balance of the pinch is strongly influenced by ohmic heating and radiation. These calculations give us important parameters such as temperature and density which in turn determine EUV output and conversion efficiency (CE). We also discuss the importance of non-LTE physics. Such effects necessitate the use of an inline collisional radiative model to more accurately determine pinch conditions and EUV output. Using these models, we discuss scaling the EQ-10 to obtain higher powers and brightness. Lastly, we discuss the modeling of alternative gases to produce 6.x nm (Blue-X) sources.

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).



P45

Characterization of 1- and 2-um Solid-State-Laser-Driven Plasma Sources of EUV Light (Invited)

Oscar Versolato

ARCNL, Science Park 106, 1098 XG Amsterdam, The Netherlands

Extreme ultraviolet (EUV) nanolithography relies on 10.6-micrometer wavelength CO₂-lasers to drive EUV-emitting tin plasma. We will present on ARCNL's research using solid-state laser light instead, at 1- and 2-micrometer wavelength, to efficiently drive plasma from various targets. Our research aims to contribute to the understanding of the physical processes involved in generating extreme ultraviolet (EUV) light from laser-produced plasma, at the fundamental, atomic level.

Presenting Author

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



Ultra-high Photon Flux High-harmonic Generation

Maxim Tschernajew¹, Steffen Hädrich¹, Robert Klas^{2,3}, Martin Gebhardt^{2,3},
Roland Horsten⁴, Sven Weerdenburg⁴, Sergey Pyatchenkov⁴,
Wim Coene^{4,5}, Sven Breilkopf¹, Oliver Herrfurth¹,
Jan Rothhardt^{2,3}, Tino Eidam¹ and Jens Limpert^{1,2,3,6}

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High-harmonic generation (HHG) driven by ultrashort laser pulses is an established process for the generation of coherent extreme ultraviolet (XUV) to soft X-ray radiation, which has found widespread use in various applications [1]. In recent years photon-hungry applications such as coherent diffractive imaging [2,3] and applications based on statistical analysis [3] have required more powerful HHG sources employing higher repetition rates. This need can be addressed by using high-average-power fiber lasers as the HHG drivers [4]. Here, we present a HHG-based XUV source providing a large photon flux across a wide range between 66 eV and 150 eV. It is driven by a commercial XUV beamline from Active Fiber Systems GmbH consisting of a 100-W average power fiber-laser system delivering up to 300 μ J at <300-fs pulse duration. For HHG, this system is operated at 100 W and 600 kHz. A post-compression unit is part of the device to shorten the pulses to approx. 35 fs, the average power remains at 63W. The turnkey source provides unprecedented photon flux of $>10^{11}$ photons/s in each harmonic between 69 eV and 75 eV (HH57-HH63). All flux values are given at the generation point of the high harmonics, i.e. directly after the source.

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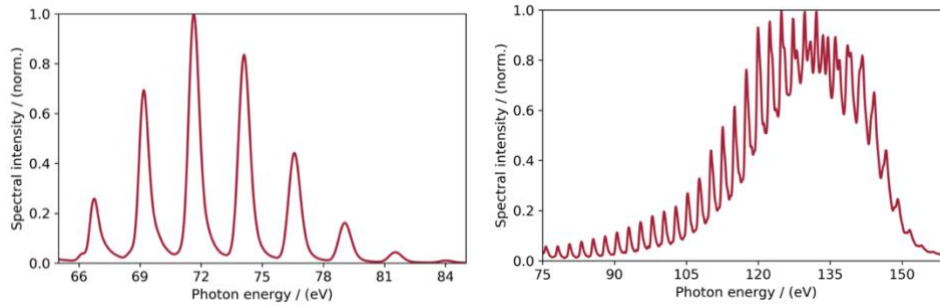


Fig. 1 Left: HHG spectrum generated in argon and optimized for ~70eV operation. Right: HHG spectrum generated in neon and optimized for operation at >92eV.

Figure 1 (left) shows a typically measured HHG spectrum using argon. The photon flux is analyzed by accounting for the transmission of the measurement apparatus (flat-field grazing incidence spectrometer) showing that the strongest harmonic (HH59) at 71 eV features $3 \cdot 10^{11}$ photons/s. This constitutes a record-high photon flux at this photon energy for any reported laser-driven source to date [5,6,7]. Therefore, it can be expected that this source will enhance and speed up applications that currently suffer from long measurement times.

A second focus of optimization is put on the spectral range around 93 eV (Fig.1 (right)), because of its significance for semiconductor industries [8]. Without changing the optical setup, the source can be tuned to this wavelength by using neon. At 93 eV, the source delivers $5 \cdot 10^9$ photons/s/(1% bandwidth), which enables numerous experiments in that important wavelength range. Generally, the source can deliver photon energies of up to 150 eV with a photon flux $>10^{10}$ photons/s/(1% bandwidth) for harmonics between 115eV and 140eV, which also constitutes a record flux in that spectral range. Generally, an important aspect of each HHG source regardless of its particular application is their user-friendliness and output stability. Over the time span of one hour, the photon flux is as stable as ~1% RMS in the spectral range around 70 eV and 90 eV, respectively.

- [1] T. Popmintchev et al. Nat Phot. 4, 822–832 (2010).
- [2] J. Rothhardt et al. J. Opt. (United Kingdom) (2018).
- [3] G. S. M. Jansen et al. Optica 3, 1122–1125 (2016).
- [4] S. Hädrich, et al. J. Phys. B At. Mol. Opt. Phys. 49, 172002 (2016).
- [5] J. Rothhardt et al. Opt. Express 24, 18133–18147 (2016).
- [6] C. M. Heyl et al. J. Phys. B At. Mol. Opt. Phys. 50, 013001 (2017).
- [7] R. Klas et al. Opt. Express 28, 6188–6196 (2020).

Presenting Author

Dr. Sven Breitkopf is Head of Sales at Active Fiber Systems GmbH in Jena, Germany. He received the Diploma degree in general physics and the Ph.D. degree from the Friedrich-Schiller-Universität in Jena, Germany, in 2011 and 2018, respectively. His research interest was focused on high average power ultrafast fiber lasers, enhancement cavities and coherent pulse combining techniques. From April 2018 to April of 2019 he was a project manager at Active Fiber Systems GmbH before being promoted to coordinate the global sales activities.



P47

Update of Tsinghua SSMB EUV Light Source Development

Xiujie Deng, on behalf of Tsinghua SSMB Task force

Tsinghua University, Beijing, China

The mechanism of steady-state microbunching (SSMB) has been experimentally demonstrated at the Metrology Light Source in Berlin ^[1]. Based on SSMB, high-average-power narrow-band EUV radiation can be generated. A compact SSMB EUV source is a promising candidate to serve the high-volume manufacturing of EUV lithography with a reasonable price. In this talk, we will present the next-step SSMB experiment program and the progress of Tsinghua SSMB EUV light source development.

[1] Nature 590, 576–579(2021).

Presenting Author

Xiujie Deng is a postdoc at Tsinghua University, Beijing, China. He obtained his Ph.D. degree in accelerator physics from Tsinghua University in 2022. His current work focuses on the physics of steady-state microbunching (SSMB), based on which high-average-power, narrow-band short-wavelength coherent radiation at a high repetition rate or in continuous-wave mode can be produced using an electron storage ring.



Modeling of EUV Spectrum of Unresolved Transition Arrays of High-Z Ions Using Theoretical and Data Driven Approach

Akira Sasaki

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Strong EUV emission at $\lambda = 13.5$ nm and shorter wavelength is obtained from laser produced plasmas. The emission spectrum shows a broad UTA (Unresolved Transition Array), which arises from a large number of individual atomic lines through $n=4$ to 4 transitions. Modeling of the spectrum has been a challenge because accurate atomic data is obtained for rather limited atomic transitions. Even these data is available, investigation of the spectrum using a model taking the full set of emission lines into account is too computationally intensive. A simple model that can represent the characteristic feature of UTA should be useful. We investigate the computational and experimental spectrum from combined 4d-4f and 4p-4d transitions from Sn to Hf to find that the wavelength of the UTA can be represented using a simple screening theory [1]. We will investigate emission spectrum from elements with higher z up to Bi, especially for UTA from open 4f ions, that exhibits spectrum with nearly continuum structure. We will also investigate the width and strength of the UTA. After the validation of the theoretical results through comparisons with the observation, we will discuss the model of plasmas of tin and heavier elements, which is applicable to the investigation of radiative transfer in the plasma.

[1] A. Sasaki et al., AIP Advances, 12, 025309 (2022).

Presenting Author

Akira Sasaki obtained Dr. Eng. from Tokyo Institute of Technology in 1991, and joined Japan Atomic Energy Research Institute in 1996, the organization of the institution has changed since to present National Institute for Quantum Science and Technology. He is interested in the modeling of atomic process and spectroscopy of the plasmas. He has developed a large-scale collisional radiative model based on the computational atomic data. He is also interested in the complex materials and its modeling using statistical methods. He has been involved in the research project for the EUV lithography since 2003, for the analysis of emission from laser produced tin plasmas.



Enhanced EUV Lighting with Optimized C-beam Irradiation

Sung Tae Yoo, and Kyu Chang Park*

*Department of Information Display, Kyung Hee University,
Dongdaemun-gu, Seoul, 02447, Korea*

Many researchers are struggling to enhance performance and generate extreme ultraviolet (EUV) light using laser-produced tin (Sn) plasma (LPP). Field emission, which emits electrons through quantum mechanical tunneling, is widely applied in electron beam lithography, scanning electron microscopy, X-ray and UV lamps, etc. with advantages such as fast switch-on time, small size and high emission current density [1]. We developed the cold cathode-based electron beam using carbon nanotube (CNT) emitters called C-beam and applied it to EUV light source. C-beam obtained large area UV lighting from UVA to UVC [2]. Recently, it was confirmed that the generation of EUV by direct irradiation of electrons to Sn target using polymethyl methacrylate (PMMA) photoresist lithography and an EUV photodiode equipped with a 150 nm thick Zr filter was used [3]. Based on these, enhanced EUV lighting was obtained by optimizing the C-beam irradiation conditions. We are going to talk about C-beam irradiation conditions and multiple C-beam irradiations, and more details will be presented at the conference.

[1] Egorov, N. & Sheshin, E. *Field emission electronics*. (Springer, 2017).

[2] Yoo, S. T. & Park, K. C. Sapphire Wafer for 226 nm Far UVC Generation with Carbon Nanotube-Based Cold Cathode Electron Beam (C-Beam) Irradiation. *ACS omega* 5, 15601-15605 (2020).

[3] Yoo, S. T. & Park, K. C. Fabrication of EUV light source with cold cathode electron beam (C-beam). *2021 Source Workshop*.

Presenting Author

Sung Tae Yoo received the B.S. degree in mechanical engineering from Chungbuk National University, Republic of Korea, in 2013 and the M.S. degree in Department of Information Display from Kyung Hee University, Republic of Korea, in 2017. He is currently pursuing the Ph.D. degree in Department of Information Display from Kyung Hee University, Republic of Korea. His technical interests are in the EUV & UV light source, field emission, carbon nanotube.



P51

Improvement of Patterning Performance in EUV Lithography (Invited)

Jung Sik Kim

SK Hynix, 2091, Gyeongchung-daero, Bubal-eup, Icheon-si, Gyeonggi-do, Korea

Introduction of Extreme Ultraviolet Lithography (EUVL) has enabled high volume manufacturing with enhanced resolution comparing to ArF Immersion lithography. The key point for the chip makers is how far the resolution limit will be extended by using the EUVL. Since the stochastic defects such as contact missing and bridges, etc. are more generated for EUVL, there are some challenges with respect to patterning performance. In order to improve the performance in EUVL, reducing k_1 is also needed and being researched such as using optimized pupil, new material resist and especially low-n mask which is the promising mask type that can reduce mask 3D effect and improves resolution.

We reviewed the patterning performance by using the normalized image log slope (NILS) of the aerial image, which indicates CD uniformity and stochastic defects in some degree and provides the difficulty of patterning performance. Thus, the rigorous simulation tool was used to calculate NILS for contact holes and line & space patterns. And also, high-NA system is analyzed by simulation since there are some difficulties in spite of the improved resolution. We believe that these results can help us find the resolution limit and discuss the challenges to improve the patterning performance of EUVL.

Presenting Author

Jung Sik Kim is a Photolithography Engineer in SK Hynix's Research and Development Division. He received an M.S. and Ph.D. degree from Hanyang University in Nanoscale Semiconductor Engineering.



P52

Berkeley MET5 Enters Mature Phase of Research (Invited)

Chris Anderson

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Cyclotron Rd, Berkeley, CA 94720*

Continued optimization and improvement of the hardware and procedures for litho, processing, and operations have brought the MET5 ecosystem into a mature phase of its research lifecycle. The past year resulted with improved focus control, improved image stabilization, improved dose calibration, improved processing, 2X increase in shift capacity, new diagnostics for exposure dose and illumination alignment, improved online tools for users to plan and run experiments, improved data security, improved consistency of wafer supply, and improved film thickness metrology. This paper provides a summary of these improvements and learnings.

Presenting Author

Chris manages the EUV materials research center at Berkeley Lab and develops EUV and x-ray optical systems used for science and research.



P53

ZEISS EUV Optics – Past, Present and Future (Invited)

Simon Bihl, Paul Graeupner, Dirk Jürgens, Jens Timo Neumann

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

Nowadays, the most recent EUV scanner NXE:3600D with a NA of 0.33 is used in high volume manufacturing to produce state of the art integrated circuits with ever decreasing feature sizes. This steady shrink of the feature size, known as Moore's law, has been the foundation of our industry for more than 50 years. The continuous resolution improvements of each generation of lithography scanners have enabled this shrink in feature size.

To further increase the resolution of EUV scanners, ZEISS and ASML are working on the next generation EUV tool with an increased NA of 0.55. In combination with a highly flexible illumination system, the high-NA scanner optics will be able to print sub 8nm half-pitch resolutions in a single exposure, supporting Moore's law beyond the next decade.

In this presentation, we will report on the status of the 0.33NA optics, of which more than 100 optics have been delivered to the customer. A short recap of the system concept of the high-NA optical column, including the anamorphic design will be given, as well as an up-to-date status of the high-NA program and production at ZEISS. This includes the mirror polishing, coating, surface-figure metrology, mirror handling and integration tooling. Progress in manufacturing of the mechanics, frames and mirrors at ZEISS for both optical components, the illuminator and the projection optics box (POB), will be shown. We will end with a short outlook of the EUV optics roadmap beyond high-NA.

Presenting Author:

Dr. Simon Bihl

2012: Physics Diploma at the University of Heidelberg

2017: Dr. rer. nat. at Max Planck Institute of Astronomy in Heidelberg

2019: Start at Carl Zeiss SMT GmbH in the group 'Product System Engineering Imaging and Illumination'



AFM of EUV Photoresist for Material Limit Characterization

Luke Long^{1,2}, Andrew Neureuther^{1,2}, and Patrick Naulleau²

1. University of California at Berkeley

2. Center for X-ray Optics, Lawrence Berkeley National Lab

With 0.55NA EUV scanners on the horizon, and random events related to photon and chemical shot noise already challenging high volume manufacturing, greater emphasis is being placed on the ultimate stochastic limits of photoresist materials. While photon shot noise is relatively well understood in terms of its contribution to LER and resist defects, chemical effects, such as those due to random PAG and quencher distributions, polymer protecting groups, acid blur, etc. remain more challenging to probe. It is these effects that, in addition to contributing to total defect counts at today's patterning doses, limit resist performance even in the presence of unlimited photons. In this work, we explore the use of atomic force microscopy on "open frame" exposed-but-undeveloped regions of photoresist to characterize exposure-induced deprotection roughness in EUV materials. These results are compared to those from our stochastic model, with the aim of understanding how component loading impacts the so-called material limit of photoresist materials.

Photoresist Roughness Understanding & LWR Floor

Joost van Bree¹, Ruben Maas¹, Paulina Rincon Delgadillo²

¹ASML, Veldhoven, The Netherlands

²IMEC, Leuven, Belgium

One of the key parameters limiting further dimensional scaling in EUV lithography is the Line Width Roughness (LWR) of features. Typically the LWR goes down with increasing optical contrast, but resist granularity and chemical noise set an intrinsic lower limit to the roughness independent of the optical contrast, the so-called LWR floor. A better understanding of the LWR floor is needed as it provides the route to reducing it and enabling further dimensional scaling. We will present on the methodology that we developed to systematically study scaling of LWR with optical contrast, and will discuss the results of a series of experiments recently performed in collaboration with imec, studying the influence of processing conditions on the LWR floor.

Presenting Author

Joost van Bree is a Researcher at the ASML Research in Veldhoven, The Netherlands. In 2014 he received his Ph.D. in Physics on the topic of spin-orbit correlated currents in semiconductor nanostructures at the Eindhoven University of Technology. During a post-doc at the University of Iowa in 2015, he invented a quantum sensing technique for detecting magnetic permeabilities. This idea was awarded a Rubicon grant by the Dutch Research Council (NWO), which enabled him to work on this concept as a post-doc at the Institute for Molecular Engineering at the University in Chicago from 2016 until 2018. In 2018 he joined ASML research, focusing on the fundamental limits of photoresist.



Performance Advances of Multi-Trigger Resist for EUV Lithography (Invited)

C. Popescu^a, G. O'Callaghan^a, A. McClelland^a, J. Roth^b, E. Jackson^b, A.P.G. Robinson^a

^a*Irresistible Materials, Birmingham Research Park, Birmingham, UK*

^b*Nano-C, 33 Southwest Park, Westwood, MA, USA.*

As the requirements for ever smaller lithographic patterns continue, the semiconductor industry has moved to patterning with Extreme Ultraviolet Lithography (EUV), which introduces a number of challenges in the design of photoresists. EUV photons have significantly higher energy and the resist is exposed by radiation chemistry routes rather than the well-known photochemistry from early lithographic nodes. In addition, resists must contend with much higher photon-shot noise, require high EUV absorbance to offset the need for very thin films, especially in High-NA EUV, where the depth of focus will be less than 20 nm, and ultimately the theoretical resolution limits of EUV will approach the size of typical photoresist molecules. We are developing a new type of photoresist based on the multi-trigger concept, which seeks to suppress line edge roughness using a new photoresist mechanism, and which is based on molecular rather than polymeric materials to maximize resolution.

Here we present results showing advancing performance outcomes due to enhancement of the high-opacity multi trigger resist system. We present a range of process conditions and formulation variations including substrate changes which impact roughness and defectivity. The lithographic performance at pitch 28nm patterned on an ASML NXE3400 scanner is presented on a variety of substrates. Lines with a width of 13nm can be patterned at 50.5mJ/cm² with a biased LWR of 4.3nm using a 20nm resist film thickness spun on the Brewer Optistack AL412 underlayer (12nm thickness). We also present results on SOG/SOC stacks and the optimization required of the substrate to improve LWR and decrease defectivity. We further present results where we have been targeting sub 20mJ/cm² patterning. Introducing an alternative PAG but maintaining constant formulation and process conditions has enabled the patterning of p32 line spaces with 16nm lines with a dose of 16.4mJ/cm² and a biased LWR of 4.75nm. p28 lines lines spaces with 12nm lines have been patterned with a dose of 17.5 mJ/cm² and a film thickness of 14.5nm. Work is continuing to reduce the LWR whilst maintaining a sub 30mJ/cm² dose. Multi-trigger resist has also been used to pattern pillars arranged in a hexagonal pattern. We show results at pitch 34nm, again patterned on an ASML

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NXE3400, patterned at $77.5\text{mJ}/\text{cm}^2$ to obtain a pillar diameter of 17nm with a LCDU of 4.3nm with a focus window of over 60nm. A film thickness of 17nm was used. For pitch 38nm pillars, we can show a defect free process window at best focus of $>\pm 5\%$ of CD. Additionally, formulation changes have shown that we can reduce the dose required for 19nm diameter hex pillars at p38 to $52\text{mJ}/\text{cm}^2$ whilst maintaining a LCDU of 3.9nm using a 26nm resist film thickness.

Presenting Author

Alex Robinson is co-founder, and Chief Technical Officer, of Irresistible Materials Ltd. He focuses on the development of resist materials for EUV, and Electron Beam Lithography, and on high-carbon spin-on materials for etching.



Experimental characterization of EUV resist materials: Photoelectron spectroscopy

Oleg Kostko, Terry R. McAfee, Patrick Naulleau

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

In EUV resists, due to the high energy of the incident photons, most of the radiation chemistry arises from the emitted electrons and not the EUV photons themselves. The absorption of an EUV photon by a resist film leads to the emission of primary electrons, which, through a cascade of inelastic scattering events, cause excitation of molecules and emission of secondary electrons. The electrons may travel up to tens of nanometers before losing their kinetic energy via collisions which initiate chemical reactions. Because the electrons are playing a leading role in EUV patterning, initiating chemical transformations, it is important to characterize their generation, transport, and energy distribution.

Previously, we demonstrated a suite of experimental techniques, capable of characterizing EUV absorption, yield and attenuation length of electrons in resist materials [1,2]. In this work we demonstrate how to experimentally investigate the energy spectrum of those electrons via EUV photoelectron spectroscopy of thin films. To understand how to control the electron cascade, we carry out photoelectron spectroscopy to explore how different elements may change the energy distribution of emitted electrons. We will provide updates on the recent advances in fundamental research of EUV resists.

[1] J. H. Ma, P. Naulleau, M. Ahmed, and O. Kostko, *Determination of Effective Attenuation Length of Slow Electrons in Polymer Films*, *J. Appl. Phys.* **127**, 245301 (2020).

[2] O. Kostko, T. R. McAfee, J. Ma, J. M. Blackwell, and P. Naulleau, *Experimental Characterization of Model Resist Materials*, in *International Conference on Extreme Ultraviolet Lithography 2021*, Vol. 11854 (SPIE, 2021), pp. 24–34.

Presenting Author

Oleg Kostko obtained his doctoral degree from the University of Freiburg, Germany in 2007, and in the same year he joined the Berkeley Lab as a postdoctoral fellow. After a short stay at SRI International, where he studied atmospherically relevant processes, he returned back to the Berkeley Lab to lead an effort for developing soft X-ray spectroscopies on nanoscale systems. He collaborates with the Center for X-Ray Optics, Berkeley Lab, advancing novel electron spectroscopies specifically to probe EUV materials.



Research Activities Including the Hydrogen Brittle Evaluation in EUVL at NewSUBARU (Invited)

Takeo Watanabe, Tetsuo Harada, and Shinji Yamakawa

Center for EUVL, LASTI, University of Hyogo, 3-1-2 Kouto, Kamigori, Akou-gun, Hyogo 678-1205, Japan

EUV research has been carried out since 1996 at the laboratory of Advanced Science and Technology for Industry, University of Hyogo. And the Center for EUVL established in Oct. 2010 at our lab.

Research of EUV resist, mask, optics and so on has been carried out with leading and joint the four national projects in Japan approximately 20 years, and collaborating with many companies inside and outside Japan.

Recently EUVL started to use in HVM. However, technical issues remain still. Especially, since the ASML exposure tool is operated at the hydrogen environment, the hydrogen brittle evaluation of mask and resist become very significant. It is introduced that the exposure tool which can evaluate hydrogen brittle of mask materials such as multilayer pellicle, and resist et al in high EUV power of 30 W/cm² at hydrogen pressure of 70 Pa. 10.8 m long undulator employed as a EUV light source which can generate high brilliance of EUV wavelength region. This undulator is the largest size in soft X-ray region. To realize the high power EUV, the beamline setup was improved. It is introduced the results of hydrogen brittle evaluations on a basis of reflectivity measurements.

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 international affair, and the organizing and program committee members, of the International Conference of Photopolymer Science and Technology (ICPST). He is also Conference Chair of the International Conference of Photomask Japan. And he is a program committee member of the International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN).



P59

EUUV Resist Challenges and Chemical Stochastics (Invited)

Greg Denbeaux

University of Albany

The ability for the EUV photoresist to reproducibly and reliably print desired features is critical to the success of EUV lithography. However, at the desired feature sizes, fundamental resist inhomogeneities leading to local variations in resist sensitivity are a critical issue. At a fundamental level, measurements have shown that the printability of large numbers of contact holes cannot simply be extrapolated from contact hole LCDU measurements since the feature sizes do not follow normal statistical distributions. Although it is mostly understood that the EUV photon stochastics will be a significant issue, the stochastics of the resist itself appear to be at least as important and minimally studied so far. So, the issues of line edge roughness (LER), edge placement error (EPE), micro and nano-bridging, and undersized and missing contact holes can be traced back to a combination of photon statistics and local resist sensitivity variations.

In order to measure the resist stochastic effects (material inhomogeneities), we have developed a process to measure the local resist sensitivity variations. The basic approach is to use a uniform exposure of low energy electrons to expose the top few nanometers of the resist with a sharp exposure contrast in depth. After this blanket exposure and development, the remaining surface profile maps inversely with the local resist sensitivity. With this approach, we can measure millions of locations and start to develop an understanding of the local resist sensitivity variations and how that could be impacting the contact printability failures with EUV resists, and deduce effects of bake time, development time, PAG concentration, and other effects that lead to local resist segregation.

Presenting Author

Greg Denbeaux received his BA degree in physics from Wesleyan University in 1993. He studied free electron lasers and x-ray microscopy for his PhD from Duke University in 1999. He was a staff scientist at Lawrence Berkeley National Laboratory until becoming faculty at the College of Nanoscale Science and Engineering, Albany, New York. Currently, he is an associate professor at SUNY Polytechnic Institute and studies fundamentals of photoresists including stochastic effects, outgassing, and secondary electron interactions. He also has a research program in nanoparticle detection, quantification, identification and transport, all aimed at defectivity reduction in semiconductor manufacturing. He has published over 200 papers on this research which have been cited over 2,500 times. He has



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organized the IEUVI Resist Technical Working Group (TWG) for the last few years.

P60

Advanced EUV Resist Patterning with Metal Oxide Resist (MOR) (Invited)

Seiji Nagahara

Tokyo Electron Limited, Tokyo, Japan

For high volume manufacturing of future technology node semiconductor devices, metal oxide resist (MOR) is one of the strong candidates as a resist material for EUV lithography. This talk will review the current status of MOR patterning processes and future outlook [1-2].

EUV stochastic defects due to EUV photon stochastics and resist chemical stochastics the remaining challenges for EUV patterning. Also, resist sensitivity enhancement, roughness reduction, and resolution enhancement simultaneously are still the key action challenges. Wafer CD uniformity improvement is also an important challenge for getting good yield on a full wafer. We will discuss new technologies which improve the performance in the above challenges.

[1] Angélique Raley, Lior Huli, Alexandra Krawicz, Steven Grzeskowiak, Katie Lutker-Lee, Yannick Feurprier, Kathleen Nafus, Arnaud Dauendorffer, Nayoung Bae, Josh LaRose, Andrew Metz, Dave Hetzer, Masanobu Honda, Tetsuya Nishizuka, Akiteru Ko, Soichiro Okada, Yasuyuki Ido, Tomoya Onitsuka, Shinichiro Kawakami, Seiji Fujimoto, Satoru Shimura, Cong Que Dinh, Makoto Muramatsu, Peter Biolsi, Hiromasa Mochiki, Seiji Nagahara, SPIE 2022, 12056-18, 2022.

[2] Seiji Nagahara, MNC2021, 2021, 28A-3-2.

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.



P61

Atomic Layer Deposition Derived Organic-Inorganic Hybrid EUV Resists (Invited)

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High-performance photoresists pose one of the critical challenges for high-volume manufacturing of extremely downscaled semiconductor devices by EUV lithography (EUVL). Hybrid photoresists containing inorganic elements have a potential to provide high EUV absorption obviating the need of chemical amplification, high etch resistance for a facile pattern transfer, and low required thickness suitable for high N.A. EUVL. In this talk, I will discuss our on-going efforts on synthesizing hybrid resists based on atomic layer deposition (ALD) and characterizing their EUV and electron exposure characteristics. Two distinctive approaches, including vapor-phase infiltration (VPI) and molecular ALD (MALD), are presented, where the former utilizes an infiltration of gaseous inorganic precursors into existing organic resists and the latter a cyclic layering of organic and inorganic molecular monolayers. Given the facile implementability and control of resist composition and characteristics, the ALD-based hybrid resist synthesis has a potential for enabling high-performance EUV resist systems.

Presenting Author

Chang-Yong Nam is a Scientist at the Center for Functional Nanomaterials (CFN) of Brookhaven National Laboratory (BNL). He is also an Adjunct Professor of Materials Science and Chemical Engineering at Stony Brook University. Chang-Yong received his Ph.D. in Materials Science and Engineering from University of Pennsylvania (2007), M.S. in Materials Science and Engineering from KAIST (2001), and B.E. in Metallurgical Engineering from Korea University (1999; leave of absence for military service during 1995 - 1997). Chang-Yong joined BNL in 2007 as a Goldhaber Distinguished Fellow and has risen through the ranks to Scientist in 2016. His current research addresses two focused areas: (a) Development and application of ALD techniques toward micro/nanoelectronics and energy technologies; (b) Materials processing and device physics in organic semiconductors and low-dimensional materials including nanowires and two-dimensional materials. His distinctions include the Winner of DOE National Labs Accelerator Pitch Event (2021), BNL Spotlight Awards (2018, 2011) and Goldhaber Distinguished Fellowship (2007).



Industrial Photoresist Qualification with a Compact EUV Exposure Tool

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In this contribution the authors present industrial photoresist qualification with a compact EUV exposure tool operating at a wavelength of 13.5 nm. The developed setup allows for fast and reproducible qualification of state-of-the-art EUV photoresists regarding contrast, sensitivity, and resolution. The patterning performance for line and pinhole patterns is evaluated down to sub-30 nm half-pitch size.

The realized exposure tool utilizes partially coherent radiation from a compact discharge-produced plasma (DPP) EUV source, operated with pure Xe and filtered to in-band EUV at 13.5 nm with 4% bandwidth (FWHM) with an out-of-band filter and a customized multilayer mirror. For partially coherent radiation as provided by the DPP source, the (achromatic) Talbot lithography has proven to be most suitable with a demonstrated resolution in the sub-30 nm regime and theoretical resolution limit below 10 nm. To create high-resolution nanopatterns on the wafer, efficient phase-shifting transmission masks need to be designed and fabricated. Different material combinations and geometries can be applied to enable highest contrast of the resulting intensity distribution on wafer.

The latest advancements in both simulation and fabrication processes for high-resolution phase-shifting masks are presented in this contribution as well as the latest exposure results in EUV photoresists with the realized exposure tool. With the presented technology we can offer a full range for industrial EUV photoresist qualification from contrast and sensitivity measurements to high-resolution nanopatterning tailored to customer's processes.

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Presenting Author

Bernhard Lüttgenau is a PhD student at RWTH Aachen University. He received his bachelor's and master's degrees in physics, majoring in the subject of solid-state physics. Since 2019, he is working in the EUV technology group at the Chair for Technology of Optical Systems. His research topics include EUV interference lithography with compact EUV sources and related process technologies.



Low-Energy Electron Exposure and Dry Etching Characteristics of Hybrid Thin Films Prepared by Molecular Atomic Layer Deposition for EUV Lithography

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One of the critical challenges of the EUV technology is the need for improving its photoresists. Current EUV photoresists used in the high-volume manufacturing are predominantly chemically amplified resists (CARs) with low EUV absorption coefficient and intrinsic resolution limit dictated by chemical blur from the diffusion of photoacid generator (PAG). Recently it has been suggested that organic-inorganic hybrid thin films prepared by atomic layer deposition could be used as high-performance, novel *dry* EUV photoresists.

Here, we investigated the low-energy electron exposure and dry etching characteristics of hybrid thin films made by molecular atomic layer deposition (MALD) of trimethylaluminum/hydroquinone to test their feasibility as a negative-tone dry EUV photoresist. We used a low-energy electron microscope to control the energy of irradiating electrons from 100 to 250 eV and investigated the critical exposure dose and contrast under wet development. In addition, we further studied the reactive ion etching (RIE) characteristics of the hybrid resist: By tuning RIE process parameters, we demonstrated a potential, negative-tone dry development process, achieving a maximum etch contrast of ~10 nm between the electron-exposed and unexposed regions. The demonstration hints at a potential of the MALD hybrid thin film approach for developing new hybrid resists for EUV lithography.

Presenting Author

Won-Il Lee is a Ph.D. student at the Department of Materials Science and Chemical Engineering at Stony Brook University, working under the supervision of Dr. Chang-Yong Nam. His research is focused on developing atomic layer deposition techniques towards materials patterning and electronic device applications.



High-sensitivity Hybrid EUV Resist Synthesis via Vapor-phase Infiltration

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Hybrid resists are proving to be an elegant alternative to traditional CARs in meeting the rigors of performance requirements for EUV lithography. While many negative-tone hybrid resist formulations have come to fruition, there has not been much progress in terms of positive-tone hybrid resists.[1] We are tackling this development gap with vapor-phase infiltration of inorganic moieties into traditional organic resists. [2,3] We have expanded the approach to infiltrate high sensitivity resist (HSR) with wider range of inorganics.[4] Progress in synthesizing compositional variants of HSR-hybrids will be presented. The effect of processing condition on evolution of sensitivity, contrast, and patterning resolution for electron-beam and EUV lithography of the HSR-hybrids will be discussed.

[1] Saifullah, Tiwale and Ganesan, JM3, in press (2022)

[2] Tiwale, Nam et al., J. Mater. Chem. C **7**, 8803 (2019)

[3] Tiwale, Nam et al., Proc. SPIE **11326**, 113260J (2020)

[4] Tiwale, Nam et al., Proc. SPIE **11612**, 116120A (2021)

Presenting Author

Nikhil Tiwale is a scientific associate (staff scientist) in Electronic Nanomaterials Group at CFN-BNL. He pursued postdoctoral research working with Dr. Chang-Yong Nam, employing infiltration synthesis for developing hybrid resists for advanced nanolithography and fabrication of nano(opto)electronic devices. He obtained his PhD from University of Cambridge in 2017 on developing direct-write EBL technique for fabricating ZnO nanoFETs and gas sensors, under the supervision of Prof. Sir Mark Welland. Before joining BNL, he briefly worked at Adaptix Ltd. as silicon process engineer.



Latent Image Characterization in Photoresists by EUV Spectrometry

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In the lithographic process, the performance of photoresists is a limiting key factor for the quality of fabricated nanostructures. The possibility to monitor the resist during processing is of major interest when it comes to linking fabrication errors to the resist behavior during each process step. For this reason, the authors investigated the use of a compact laboratory-based EUV spectrometer for the characterization of latent images in an EUV photoresist, which can be applied throughout the lithographic process.

The utilized setup uses a discharge-produced plasma EUV source providing broadband emission between 5 nm to 20 nm to measure the broadband reflectance of samples for various grazing incidence angles. Based on the measured reflectance data, information on changes of the layer thickness and optical constants of the photoresist is reconstructed, which is related to the resist processing.

It is demonstrated that for a chemically amplified resist a change of the optical constants due to post exposure bake is detectable, which opens the way to characterize latent images of nanostructures in the resist itself before resist development.

Presenting Author

Since 2019 Sophia Schröder works as a research assistant at the RWTH TOS – Chair for Technology of Optical Systems - in the field of EUV technology and metrology with focus on EUV spectrometry and scatterometry. She graduated with a master's degree in physics from RWTH Aachen University.



Aperiodic Multilayers as EUV Mask Mirrors

Andrey Yakshin¹, Marcelo Ackermann¹

Gerardo Bottiglieri², Mark van de Kerckhof², Jan van Schoot²

1: XUV Optics Group, MESA+ Research Institute, University of Twente

2: ASML Netherlands B.V.

EUV Lithography systems operating with 13.5 nm light have successfully been developed and built, and techniques to improve the resolution have been identified. EUV exposure systems used in production have an NA of 0.33, enabling a 13nm half-pitch for dense lines. More advanced system, with an NA of 0.55 and enabling an 8.0nm half-pitch resolution, are projected to be introduced in production in 2025.

To enable the further dimensional shrink that might be needed beyond 2030, ASML and ZEISS are exploring the possibility of further increasing the NA by developing the design concepts and solutions implemented for the 0.55NA. Within the design constraints set to preserve productivity and compatibility with the current 6-inch mask infrastructure, an increase in NA will result in an increase of the angles of the light on the mask. The maximum angle of incidence is projected to reach $\sim 13.5^\circ$, an increase of $\sim 2.5^\circ$ from the 0.33 and 0.55 EUV systems.

EUV masks are reflective and the mirror below the patterned features consists of a periodic repetition of typically 40 Mo/Si bi-layers. Such mirrors show a uniform and acceptable reflectivity ($>60\%$) for angles up to $\sim 8^\circ$. The angular acceptance can be increased by mildly adjusting the period of the bi-layers to have their peak reflectivity at a wavelength slightly larger than 13.5nm. This is how mask multilayers for the 0.33NA/0.55NA are made. The price is paid both in a less uniform ($\sim 5\%$ variation) and lower peak reflectivity. To meet the even larger angular range, periodic multilayers (PML) can be further detuned, at the cost of additional reflectivity variation (10-15%) and losses ($- 5\%$) compared to 0.33/0.55 NA.

Another possibility is to adopt a multilayer explicitly designed for a broader angular reflectance, as used in other X-ray and EUV optics applications. To ensure a uniform reflectivity these broadband multilayers require non-monotonic variations of the bilayer period and are referred to as "aperiodic multilayers" (AML). In a higher-NA system, AMLs have the distinct

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advantage that they allow different levels of trade-off between average reflectance and reflectivity uniformity, which is not possible with PML. In this work we are evaluating the use of AMLs as EUV mask reflector. Evaluation of the effect on image contrast and other lithographic figures of merit is presented.

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Confessions of an EUV Skeptic (Keynote)

Ralph R. Dammel

EMD Electronics, 3050 Spruce St., St. Louis, Missouri 63103

I have a confession to make: I have been an EUV resist denier. I have been one of the “never gonna happen” crowd. Now that EUV is in production, it is high time for me to admit: I was wrong. And I need to do it in the first person singular, I need to break with the convention of scientific impersonality. It cannot be “the author may have been in error,” it has to be: “I was wrong.” I feel I have to do this to apologize to all the members of the EUV community that I have heaped scorn on, privately and sometimes not so privately, that I have accused of “drinking the EUV KoolAid.” Their ingenuity and persistence has made EUV happen. So it is that I now find myself giving a keynote at the EUVL Workshop in which I will sing the praises of EUV lithography with the zeal of the newly converted. I have gone from EUV Saul to EUV Paul, and as in the original case all it took was a really strong light source.

Besides the spectacle of me publicly falling on my sword, this presentation will recapitulate how some of the past main obstacles for EUV implementation were overcome. It will continue to explore existing areas in which substantial improvement is still required, in particular EUV photoresists which have become the #1 critical issue in EUV lithography. It will go on to look at the imminent introduction of high NA tools and their impact on other technology components, and it will conclude with an outlook on possible extensions of EUV lithography to shorter wavelength.

Presenting Author

Ralph R. Dammel (*April 29, 1954) received a Ph.D. in Chemistry from the J.W. Goethe University in Frankfurt/FRG in 1986. He has worked for EMD Performance Materials/Merck KGaA or its predecessor organizations in Germany, the US, Hong Kong, and Thailand since then, and is currently employed as Technology Fellow in the CTO Office of Merck KGaA's Electronics division.

Dr. Dammel is the author of over 200 scientific papers in chemistry and microlithography and is an inventor on over 470 patents in over 100 patent families in the field. His monograph “Diazonaphthoquinone-based Resists” is generally recognized as the definitive book on the subject. In spring 2009, Dr. Dammel was elected as SPIE Fellow. He received the Photopolymer Science and Technology Outstanding Achievement Award in June 2011, SPIE's Frits Zernicke Award for Microlithography in February 2015, and Merck KGaA's Science Award in 2020.



EUV Manufacturing for the Next Decade (Keynote)

Michael Lercel

ASML, Veldhoven, Netherlands

Scaling has enabled the semiconductor industry to be vibrant and growing for decades. Current market drivers continue to show a current and future strong demand for semiconductors. So the long term industry outlook is good. Advanced patterning is dependent on having the right lithography, process, and metrology tools. Printing small features is not enough – tight control of tolerances, good yield, and cycle time are essential for manufacturability.

EUV is now positioned to enhance logic and memory processes with improved cycle time, less variability from multiple processes, and reduced process complexity compared to multiple patterning. Production with EUV is underway, so now the question becomes how does EUV enable the 3nm node and beyond.

EUV layer adoption is anticipated to increase at 3nm logic node versus where it is being first introduced. Beyond the 3nm logic node, higher Numerical Aperture (NA) EUV will further extend EUV single exposure resolution to enable Moore's law scaling for the rest of the decade.

In this presentation, we review the progress on enabling EUV for logic and memory manufacturing with progress on productivity, overlay performance, and availability of the EUV scanner plus the metrology and infrastructure progress to enable high-volume manufacturing. The extensions to enable EUV for upcoming logic nodes, and the preparation of high-NA EUV for 3nm and beyond node logic will be reviewed.

Presenting Author

Michael Lercel is Director of Worldwide Strategic Marketing at ASML. He obtained his Ph.D. in physics from Cornell University. After graduation, he joined IBM Microelectronics working in positions in advanced photomask development, lithography research, and leading microelectronics equipment strategy. He joined Cymer in 2010 as Senior Director for EUV Product Marketing and was at SEMATECH in various positions including Lithography Director and Chief Technologist before joining ASML in 2015.



Generation of Wrinkles and its Effect on the Performance of EUV Pellicles

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EUV-IUCC (Industry-University Collaboration Center) is a non-profit organization supported by industry members. EUV-IUCC was organized in September 2019 to help member companies to initiate their business in the field of EUV Lithography through providing information, education, networking and research collaboration.

During the presentation, our recent research activities in the field of pellicle and the research facilities to evaluate the effects of wrinkles on the mask imaging performance will be introduced.

ASML presented a specification of maximum local tilt angle of EUV pellicles for the CD uniformity. Here at EUV-IUCC, we investigated the wrinkle profile generated under the exposure process as a function of emissivity and thermal expansion coefficient (CTE) using ANSYS 2021R1 simulation tool. Furthermore, the effects of the wrinkles on mask imaging performance were experimentally investigated by coherent scattering microscope (CSM). It is speculated that the local CD change as large as 6 nm is due to a local increase in EUVR (larger than 4 times) and randomly altered beam path at the wrinkled region.

Presenting Author

Dong Gi Lee is pursuing a Ph.D degree in Materials Science and Engineering at Hanyang University. His research topic is actinic inspection technology for EUV mask and pellicle evaluation. He received his BS degree from Kumho National University in 2020.



SS4

Ultra-Sensitive Indium based EUV resist for High-NA Extreme-Ultraviolet Lithography Applications (Invited)

Manvendra Chauhan¹, Sumit Choudhary¹, Satinder K. Sharma^{*1}, Kenneth. E. Gonsalves^{2*}

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Indian Institute of Technology (IIT), Mandi, MANDI-175005, (Himachal Pradesh), India*

The semiconductor industries have been compelled to support high numerical aperture (NA) extreme-ultraviolet lithography (EUVL) systems on a commercial scale mass production due to the remarkable advancement of electronics devices integration meant for next-generation (NG) information processing and data storage applications as outlined by ITRS.^{1,2} One of the primary snags for the adoption of high-NA (0.5) for EUVL, high-volume manufacturing (HVM) of future technology nodes, is the scarcity of highly sensitive EUV resists.^{2,3} In this regard, a newly designed and developed Indium-based metal-organic cluster (In-MAA MOC) resist offers a tradeoff between resolution, roughness, and sensitivity (RLS) that directs the resist performance towards high-NA (0.5), EUVL applications. In-MAA, MOC resist exhibits ultra-high sensitivity of 2.3 mJ/cm² towards 92eV energetic EUV photons ($\lambda = 13$ nm) and resolved 26 nm half-pitch line patterns. The computed line edge roughness (LER) values are 2.36 ± 0.16 nm for well-resolved dense line patterns developed after EUV exposure. Also, it shows a high etch resistance i.e. ~ 1.98 times lower etch rate than silicon. All of these trades of In-MAA MOC resist serve as a potential candidature for the next-generation EUV resist for HVM.

- [1] Gargini, P.; Balestra, F.; Hayashi, Y. Roadmapping of Nanoelectronics for the New Electronics Industry. Appl. Sci. 2022, 12 (1), 308.
- [2] van Schoot, J.; Troost, K.; Bornebroek, F.; van Ballegoij, R.; Lok, S.; Krabbendam, P.; Stoeldraijer, J.; Loopstra, E.; Benschop, J. P.; Finders, J.; Meiling, H.; van Setten, E.; Kneer, B.; Kaiser, W.; Heil, T.; Migura, S.; Kuerz, P.; Neumann, J. T. High-NA EUV Lithography Enabling Moore's Law in the next Decade. In SPIE; 2017; p 30.
- [3] Zahlten, C.; Gräupner, P.; van Schoot, J.; Kuerz, P.; Stoeldraijer, J.; Kaiser, W. High-NA EUV Lithography: Pushing the Limits. In SPIE; 2019; Vol. 11177, p 43.

Presenting Author

Manvendra Chauhan received his B. Tech. degree in electronics and communication engineering from Invertis Institute of Engineering and Management (IIEEM), Bareilly, India in 2014 and M. Tech in Digital electronics from Madan Mohan Malaviya University of Technology (MMUT), Gorakhpur, India in 2018. He is currently working towards the Ph.D. degree with school of computing and electrical engineering at Indian Institute of Technology (IIT) – Mandi, Himachal Pradesh, India. His research interests include advance lithography, fabrication/characterization and reliability of semiconducting materials for CMOS applications.



SS5

Preparing For the Next Generation of EUV Lithography at the Center for X-ray Optics (Invited)

Ryan Miyakawa

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

The Center for X-ray Optics (CXRO) at Berkeley Lab has been a leader in EUV research for the past 25 years. Leveraging 13.5-nm EUV light from the Advanced Light Source synchrotron facility, CXRO is home to several EUV research tools that continue to provide important research insights into EUV resists, masks, metrology, and coatings. The 0.5-NA MET5 projection lithography tool and DCT2 continue to assist in the development of state-of-the-art resists. The SHARP microscope, with its customizable zone plate optics, can implement the optical geometry of next-generation EUV scanners to study mask 3D (M3D) effects and perform metrology on novel absorbers. The radiation chemistry program is deploying several techniques aimed at dissecting the role of primary photo-electrons and secondary electrons in EUV resists. And the reflectometer is designed to measure both multilayer reflectivity as well as scattering profiles for the purpose of further understanding M3D effects using scatterometry. In parallel with these tools, the CXRO wavefront sensing program continues to develop high-resolution wavefront sensors suitable for measuring aberrations at high NA. This paper presents an overview of these programs and describes how they will address the primary challenges that face the EUV community as it moves to the next generation of EUV lithography.

Presenting Author

Dr. Ryan Miyakawa is a research scientist at the Center for X-ray Optics at LBNL where he works on the Berkeley MET5 and the SHARP EUV microscope. Ryan's interests include optical design for lithography and imaging, and high-NA wavefront sensing.



SS6

Synchrotron-radiation Based EUV Metrology at PTB (Invited)

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Frank Scholze

*Physikalisch-Technische Bundesanstalt (PTB), Abbestraße 2-12, 10587
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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 X-ray. 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 Ellipso-Scatterometer 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.

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Presenting Author

Richard Ciesielski received his Ph.D. from LMU Munich (on time-resolved microscopy) in 2016. Since 2020 he is a scientist at PTB focusing on Metrology with synchrotron radiation. His research activities are centered around the determination of optical constants and the reconstruction of nanoscale grating structures from EUV scatterometry.



SS7

TNO EUV materials research for EUV infrastructure (Invited)

H.H.P.Th. Bekman, C-C. Wu, J. Stortelder, N. Koster,

TNO, Stieltjesweg 1, 2628 CK Delft, The Netherlands

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

Presenting Author

Herman Bekman holds a Ph.D. in physics from the University of Amsterdam. His thesis deals with EPR-ENDOR studies on oxygen defects in semiconductor material.

After graduation he joined TNO in 1992 and worked on integrated electro-optic Mach-Zehnder interferometer sensors using hybrid integration of AlGaAs lasers on silicon motherboards.

Since beginning of 2008 he joined the department within TNO working on EUV optics lifetime for ASML and Carl Zeiss. He has been active in various fields from modeling contaminant growth to the development of mitigation hardware that was integrated in the EUV lithography scanners of ASML.

As senior scientist he is responsible for strategy development in the nano-instrumentation department, and he is lead expert in a number of B2B project for ASML and Carl Zeiss as well as leading a European project in which plasma material interactions are being studied.



Systems for Development and Accelerated Testing of EUVL Components (Invited)

Jochen Vieker and Klaus Bergmann

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

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

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

The talk will focus on the **Fraunhofer high Irradiance Tool (FIT)** for testing of optical components. It is based on our proven FS5440 high power EUV source, whose emission is focused on a sample in controllable atmosphere. Using strong vacuum separation and particle mitigation, an extremely low operating pressure at the irradiation position can be achieved without pumping orifices in the vicinity of the focal spot. Thus, clean, unbiased experimental conditions can be achieved. The expected performance of the FIT includes: EUV irradiance $>40 \text{ W/cm}^2$, angle of incidence on sample $<5^\circ$, spot diameter $>1.8 \text{ mm}$ and pulse repetition rate up to 2.5 kHz. The design of the system allows multiplexing to reach 10 kHz and a higher power on sample. An updated design and new results based on optical and gas-flow simulations will be presented.

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 sources and secondary sources based on laser radiation as well as their applications



SS9

Multitrigger (MTR): Making a “Negative” Positive (Invited)

Warren Montgomery^{1,2},

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²MWM Strategic Development Solutions, PO Box 873669, Vancouver, WA 98687

EUV has finally broken into manufacturing in earnest. Chip makers like Samsung, Intel and TSMC are purchasing all the EUV scanners that ASML can produce. The newest EUV photoresist, including Irresistible materials photoresist are negative tone systems. MTR series photoresist is in the process of being scaled and can now be available in early production quantities.

The technology is called “the multi-trigger concept (MTR)” and is characterized by a reaction that will only occur when multiple elements of the resist are initiated concurrently and in close spatial proximity. The multi-trigger material previously presented consists of a base molecule and a crosslinker, which represent the resist matrix, together with a photoacid generator (PAG). Research has been undertaken to improve this resist, in particular focusing on improving resist opacity and crosslinking density. LER figures below 3 nm for lines and spaces patterned at 14 nm half-pitch using the high opacity MTR resist on the EUV-IL exposure tool at PSI will be shown.

I will explain why using MTR presents a low cost of ownership option. At the same time, I will show some fundamental advantages of MTR over the current Chemically Amplified Resist (Car).

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Presenting Author

Warren currently working with Irresistible materials in several roles. He is doing account management, technical materials development, commercialization and strategy. Formerly, as VP of Technical and Consortia Program Development at CNSE (formally Albany Nanotech), Warren led process development efforts associated with new photoresists focused on EUV lithography. Prior to CNSE, Warren worked at Applied Materials, LSI Logic, ASML, AZ Microelectronic and IBM in various technical and leadership roles related to photoresist processes and lithography. During his extensive career in Lithography, Warren has written over 50 technical and marketing publications and been awarded 30 US and European patents: primarily focused on lithography materials and processes. Warren served as BACUS President and Conference Chair and is, presently, a member of the EUVL Infrastructure Supplier Board.

He has a B.S. in Chemistry from Marist College, a B.S. Business Administration from Mount St. Mary College, a graduate certificate in Program Management from SUNY Empire State College and an MBA from City University.



SS10

Chemical Identification of Sub-20 nm Defects and Monolayer Residues with Nano IR PiFM (Invited)

Derek Nowak¹, Brian Grenon², Tom Albrecht¹, Sung Park¹

1. Molecular Vista, San Jose, CA

2. Grenon Consulting Inc., Forest Grove, OR

With the advent of 45nm and below technology nodes and EUV lithography, the need to identify the chemical composition of defects is of paramount importance. The defects of concern range from 10nm to 500nm and ultrathin residue, which the current batch of molecular analytical tools cannot address adequately since the indications are that many of the defects and residue detected are organic in nature. 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 ~ 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; PiF-IR spectra can be used to search the existing IR database to unambiguously identify the different chemical species (both organic and inorganic molecules) of sub-20 nm defects and monolayer residues via their IR signatures. PiFM images at fixed wavenumbers associated with the different chemical species provide chemical mapping in real space with ~ 5 nm spatial resolution, clearly illuminating multi-component defects and existence of residues. The talk will show how the nanoscale hyperspectral PiFM data can provide unambiguous and speedy feedback to process engineers engaged in EUV lithography

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.



SS11

Vacuum Processing Equipment for EUVL – From Small Substrates to Huge Optics (Invited)

Matthias Nestler

scia Systems, Clemens-Winkler-Straße 6c, 09116 Chemnitz, Germany

Scia Systems provides a wide portfolio of precise surface processing equipment based on advanced ion beam and plasma technologies. Especially for EUVL applications we designed equipment for processing of various substrates, some up to three meter in diameter, and some for smaller substrates on wafer size level. We provide systems for Mo/Si multilayer deposition, reactive ion beam etching, ion beam figuring for optical surfaces and high-quality dry cleaning and qualification. New developments for adaptive optics will also be presented.

Presenting Author

Matthias Nestler hold a diploma degree in Physical Engineering from West-Saxonian University of Applied Sciences Zwickau. In 2000, after his graduation, he worked as project manager for ion beam systems in a company specified in ion beam and plasma process technologies. In 2004 Matthias took the position of the product manager of this technology field.

He joined scia Systems as Director of Products and Technologies right from the beginning in 2013, where he is responsible for all product and process development activities.



SS12

Veeco Ion Beam Deposition Technology for EUV Photomask (Invited)

Meng Lee

Veeco, 1 Terminal Drive, Plainview, New York 11803, USA

EUV Photomask manufacturing demands the highest levels of particle control while depositing sophisticated multiple-layer film structures and Ru capping layer. These challenges are met with Veeco's Ion Beam Deposition System (IBD-LDD).

IBD-LDD key benefits:

- Production-proven platform
- Lowest defect density
- Excellent uniformity and repeatability
- High reflectivity
- Deposit multiple materials in same chamber
- Can be integrated into other process modules into a cluster tool

This presentation provides an overview and roadmap of Veeco Ion Beam Deposition technology enabling future EUV photomask requirements.

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.



SS13

From EUV to SXR: Next-Gen Metrology and Inspection Sources

Bill Solari

Energetiq Technology, Wilmington, MA, USA

As a leader in extreme ultraviolet (EUV) source development, Energetiq has over 50 sources in the field being used in materials research and high-volume manufacturing applications. Next generation metrology and inspection sources need higher power, higher numerical aperture (NA) and more brightness. Beyond EUV, emerging soft x-ray (SXR) technology is unlocking a small footprint alternative to synchrotrons with a lower cost-of-ownership and higher availability. This showcase will address the challenges of current technology and solutions that will reveal the future of metrology and inspection sources.

Presenting Author

Bill Solari is a Senior Product Marketing Manager at Energetiq Technology, focused on new product development for the Semiconductor and Life Sciences markets. Prior to joining Energetiq Technology, Bill served in a variety of process Engineering product management and technical marketing roles at Veeco Instruments, Samsung Electronics, and ASM NEXX.

Bill holds a Bachelor of Science degree in chemical engineering from Clarkson University.



SS14

25 Years of EUV Multilayer Optics at Fraunhofer IOF and OXF

Torsten Feigl, Marco Perske, Hagen Pauer, Tobias Fiedler, Philipp Naujok, Klara Stallhofer, Tina Seifert, Ernesto Roa Romero, Annika Schmitt

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After more than 20 years of fascinating, intensive and expensive research and development in universities, research labs, and industry around the world, extreme ultraviolet photons finally found their way into semiconductor fabs. EUV Lithography using a wavelength of 13.5 nm currently supports high-volume chip production at major semiconductor companies. While current EUV tools are printing wafers at a numerical aperture of 0.33, the next generation of EUV tools will operate at NA of 0.55.

25 years ago, Fraunhofer IOF started the very first project on EUV multilayer development. This paper summarizes highlights of this exciting journey from the first still low reflecting multilayer coating made in 1998 to today's 15 million € investment in optiX fab's EUV optics fab.

SS15

Rigaku EUV Optics and Detector Technology

Peter Oberta

Novodvorská 994, Praha 4, 142 21, Czech Republic

This commercial presentation is an overview of the EUV applicable optics and detectors RITE can offer. RITE was established in 2008 as a Rigaku Corporation R&D center in Europe. One of the three RC research units worldwide. RITE is producing lens coupled and fiber coupled X-ray cameras. The lens coupled camera has the highest real spatial resolution on the market. Another core product is replicated optics, which is a rotationally symmetric optics used as a collector (elliptical shape) or collimator (parabolic shape). Newly available is also Wolter shape optics. Various metallic single layer coatings, including e.g. gold and ruthenium, are available.

Presenting Author

Peter Oberta made his PhD in physics in the field of X-ray optics. Has working experience from the Swiss Light Source, where he was responsible for optics beamline layout design. At Rigaku his responsibilities are sale and R&D project management.



