2021 EUVL Workshop

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Workshop Abstracts

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Abstracts

(Listed by Paper number)

P1

Quantum Computing- A Brief History and Current Status (Keynote Presentation)

John D. Gillaspy

National Science Foundation, Alexandria, VA

Is quantum computing the "next big thing" in microelectronics? What is going on in industry, academia, and the national labs in this area today? What is the status of the National Quantum Initiative? How much money are the federal funding agencies spending on this topic? How is the field evolving, and how can I get involved? This talk will present some facts that may help you formulate your own answers to these and other questions related to quantum computing.

Presenting Author

John Gillaspy was the leader of the Plasma Radiation Group at NIST from 1999-2006, and for several years during that period served as Chair of the International SEMATECH Fundamental Data Working Group for EUV Lithography. He has published over 130 papers on a wide range of interdisciplinary topics. He currently serves as Program Director for Atomic, Molecular, and Optical Physics at the National Science Foundation, where he supports over 150 research groups at nearly 100 universities across the U.S. He is a Fellow of the American Physical Society, and has a B.S. and Ph.D. in Physics from Stanford and Harvard, respectively.

P2

EUV Ecosystem Expansion into DRAM Manufacturing (Keynote Presentation)

Stephen D. Snyder

Micron Semiconductor Inc., 8000 S Federal Way; Boise, ID 83707

Steve Jobs once said, "Great things in business aren't done by one person. They are done by a team of people." Enabling EUV Lithography for high volume manufacturing of logic devices was not the accomplishment of a single person or even a single company. It was a multifaceted collaboration spanning decades. While there certainly are applications for EUV in logic manufacturing that translate well into the DRAM space, that is not the whole story. There are also problems specific to DRAM manufacturing that need to be addressed. Innovative solutions to these problems will require collaboration throughout the EUV ecosystem. Addressing them efficiently will continue to pave the way to adoption of EUV lithography into DRAM manufacturing.

Presenting Author

Stephen Snyder has been working on lithography and patterning process development for semiconductor manufacturing for almost 9 years. His career began in the Logic Technology Development division at Intel in 2012 where he worked on 22nm, 14nm, 10nm, 7nm and 5nm Logic nodes. During his tenure at Intel, he worked on enabling low metal/contact level lithography for 10nm and FEOL patterning pathfinding for 7nm/5nm nodes. A career change in 2020 landed him in Technology Development at Micron in Boise, ID as a Photolithography Pathfinding Engineer. This role has been mostly dedicated to enabling scaling roadmaps for DRAM and Emerging Memory technologies. He has a B.S in Physics and Theoretical Physics & Applied Mathematics from Loyola University Chicago and a Ph.D. in Physics from the University of Minnesota.

P3

High-NA EUV Progress and Outlook (Keynote Presentation)

Jan van Schoot

ASML Netherlands B.V, The Netherlands

While EUV systems equipped with a 0.33 Numerical Aperture (NA) lens are increasingly being applied in high volume manufacturing, ASML and ZEISS have in parallel ramped 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, especially for managing the needed extreme low defect printing rates while maximizing the effective throughput for patterning economics. The imaging performance is being simulated based on expected surface figures of the illumination and projection optics. A path towards extending the capabilities of the high-NA system by reducing the imaging k_1 with advanced masks and illumination options will be outlined. Next to this, an update will be given on the status of the developments at ZEISS and ASML. Buildings, cleanrooms and equipment are being constructed, mirror production is ramping up, many tests are carried out to ensure a smooth implementation.

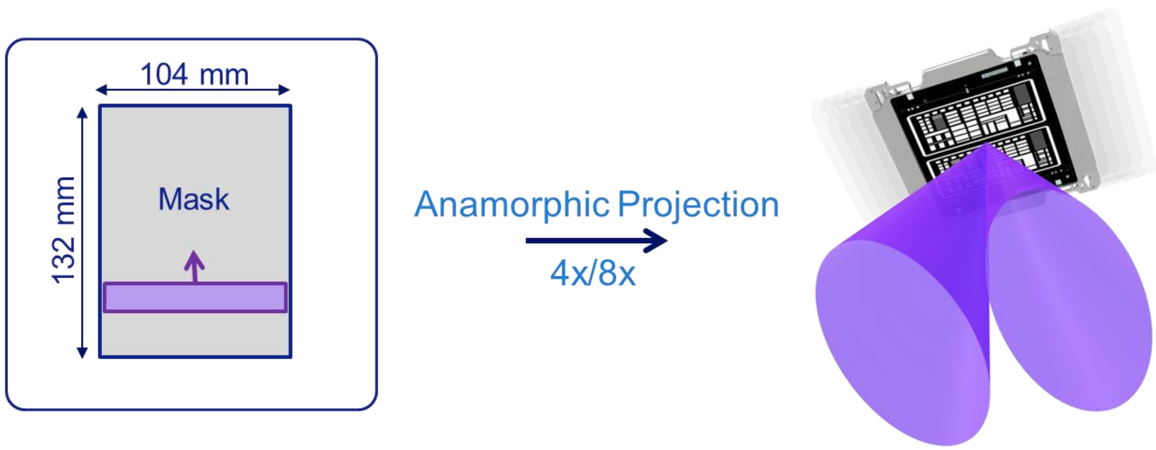


Figure 1: The High-NA exposure tool leaves the mask unchanged by limiting the angles of the light on the mask, despite the larger NA. The resulting lens has a circular pupil at the wafer, allowing for 8nm resolution, irrespective of the orientation of the features.

Presenting Author

Jan B.P. van Schoot, PhD, is Director of System Engineering and Technical Specialist at ASML, based in Veldhoven, The Netherlands.

After his study Electrical Engineering (Cum Laude) at Twente University of Technology. He received his PhD in Physics on the subject of non-linear optical waveguide devices in 1994 and held a post-doc position studying waveguide based electro-optical modulators.

He joined ASML in 1996 and was Project Leader for the Application of the first 5500/500 scanner and its successors up to 5500/750. In 2001 he became Product Development Manager of Imaging Products (DoseMapper, Customized Illumination). In 2007 he joined the dept of System Engineering. He was responsible for the Optical Columns of the 0.25NA and 0.33NA EUV systems. After this he worked on the design of the EUV source. He was the study leader of the High-NA EUV system and is now responsible for the High-NA optical train.

He is a Sr. Member of the SPIE, holds over 35 patents and presents frequently at conferences about photolithography

P4

Potential of EUV for High-volume Manufacturing of DRAM (Keynote Presentation)

Chang-Moon Lim

SK hynix,
2091, Gyeongchung-daero, Bubal-eup, Icheon-si,
Gyeonggi-do, 17336, Korea

We are genuinely living in EUV HVM era, when several tens systems were shipped out a year from an equipment maker and even larger number of them are under operation at multiple places. That is mostly owing to the aggressive adoption by logic and foundry industry, while introduction into memory sector lags little bit behind. Memory maker also has been interested in development of this technology and has poured enormous effort to utilize it for high volume manufacturing since long ago. In the presentation, briefly we will review on what specific aspects has differentiated the memory sector from logic and foundry in view of EUV adoption and will address about the current situation and potential of EUV lithography for HVM of DRAM.

Presenting Author

Chang-Moon Lim has worked in various lithography technology and process development for semiconductor memory manufacturing for almost 30 years in SK hynix. He has lead the development activity of EUV lithography in the company up to now as a research fellow. He has published over 50 papers on semiconductor lithography technology including EUV topics and has given many presentations on various conferences. He has a B.S. and Ph.D. in Physics from Seoul National University and KAIST, respectively.

P5

EUV Lithography in Volume Manufacturing and Future Extensions (Keynote Presentation)

Steve Carson

Intel Corporation

Extreme Ultraviolet lithography equipment is maturing to a level that enables replacement of 193nm-immersion as the leading-edge lithographic technology and simplifying complex integrated process strategies. For EUV to be a successful replacement in high volume manufacturing, the current successes of EUV technologies must be maintained, while the challenges that remain need to be addressed. As always, the requirements for future nodes drive increasingly aggressive targets that are creating new challenges for EUV technologies. In this presentation, the status of EUV in high volume manufacturing will be reviewed. In addition, the challenges for 0.33NA extension and 0.55NA insertion will be discussed.

Presenting Author

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

P11

EUV Masks: Prospects and Challenges (Invited)

Vicky Philipsen, Devesh Thakare, Joost Bekaert, Peter De Bisschop, Joern-Holger Franke, Andreas Frommhold, Emily Gallagher, Rik Jonckheere, Tatiana Kovalevich, Lieve Van Look, Vincent Wiaux, Eric Hendrickx

imec, Kapeldreef 75, B-3001 Leuven, Belgium

As the understanding of the EUVL grew, its different components – e.g., resist, scanner optics, source - are being tailored to create the perfect aerial image and robust resist pattern. Since recent years, the attention is moving more and more to the EUV mask. Mask specific challenges involve mask deficiency induced stochastic failures, the anamorphicity of high-NA EUVL and mask 3D effects. Pellicle development and mask lifetime understanding are well progressing to control mask deficiency impact on wafer. Stitching enablement for anamorphic imaging has been investigated leading to exclusion band recommendations.
Mask 3D effects, as a common denominator for inherent pitch- and orientation-dependent wafer observations, are identified to limit wafer performance for current and future technology nodes of 32nm pitch and below. Industry is also striving to increase the throughput, but such a dose reduction can only be applied if the aerial image quality allows.

Initial solutions to improve the aerial image are proposed by source-mask optimization, where the illumination and mask design are compensating these wafer effects, which are in fact due to the choice of the mask materials. Therefore, we have been studying different mask concepts, including different materials, from lithographic perspective and experimental mask material characteristics.

In this presentation, we will share our imaging insights in this imminent EUV-mask technology change and highlight possible directions and challenges.

Presenting Author

Vicky Philipsen received her PhD degree in solid-state physics from the University of Leuven (Belgium) in 2001. At imec she joined the Advanced Patterning department, where her research domain involves the study of mask 3D imaging effects in lithography (from 193nm to EUV and high NA EUV) both by simulations and experiments. She is leading the project on novel EUV mask absorbers at imec, including the technical task responsibility in European projects.

P12

Comparison of Deposition Techniques for Mo/Si Multilayers for EUV Mask Blanks (Invited)

Antonio Checco

Veeco Instruments, 1 Terminal Drive, Plainview NY 11803

Secondary ion beam deposition (IBD) is the process-of-record for deposition of Mo/Si multilayers for the reflective coating of EUV mask blanks. IBD has been the method of choice for at least 25 years, demonstrating outstanding performance for defectivity, central wavelength control, and EUV-reflectivity.[1] As EUV transitions into high-volume manufacturing, we assess the viability of alternative Mo/Si deposition techniques. Optical calculations indicate that EUV reflectivity can be impacted by a few percent by: (a) Mo film purity; (b) Mo/Si interfacial roughness and (c) Mo/Si interfacial intermixing. We present film properties for single and multilayers deposited by IBD, DC magnetron sputtering, and biased-target ion beam deposition. We compare film purity, microstructure, interlayer roughness and interlayer intermixing. We present x-ray diffraction, x-ray reflectivity and x-ray fluorescence; bright-field and dark-field TEM; and Rutherford Back-Scattering data.
Simulations can estimate the energetics of the depositing adatoms, and the resulting interfacial properties. We have previously demonstrated good agreement between the simulated results and TEM measurements.[2] Here we extend these simulations to estimate theoretical limits on intermixing via the three deposition techniques.

[1] P. A. Kearney, C. E. Moore, S. I. Tan, S. P. Vernon, R. A. Levesque, Mask blanks for extreme ultraviolet lithography: Ion beam sputter depostiion of low defect density Mo/Si multilayers, JVST B 15(6) (1997).
[2] Katrina Rook, Paul Turner, Narasimhan Srinivasan, Tania Henry, Kenji Yamamoto, Process optimization for performance improvement in Mo/Si multilayers for EUV mask blanks, Proc. SPIE 11517 (October 2020).

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

P13

Efficient Modeling and Correction of High-sigma EUV Stochastic Defects (Invited)

Zachary Levinson[a], Yudhishthir Kandel[b], Ryan Chen[c], Yunqiang Zhang[d], Rob DeLancey[c], Makoto Miyagi[a], Kevin Lucas[a]

[a]Synopsys Inc., 1301 S MoPac Expy Bld 4 # 200, Austin, TX 78746;
[b]Synopsys Inc., 1101 Slater Road, Brighton Hall Suite 300, Durham, NC 27703
[c]Synopsys Inc., 2025 NE Cornelius Pass Rd, Hillsboro, OR 97214
[d]Synopsys Inc., 690 E Middlefield Rd., Mountain View, CA 94043

The quality of an optical lithographically transferred pattern is dependent on the uniformity of photon absorption events that a photoresist pattern receives during exposure and the uniformity of the subsequent molecular events in the photoresist. Process variation, and subsequent control thereof, is not new to lithographers. For example, the resist film thickness, the molecular weight of resist components, and hotplate temperatures all have inherent variation. Additionally, photon statistics become increasingly important as the photon count of the incident light decreases. The photon absorption event is the first in a chain of stochastic processes in a lithographic process. These stochastic processes occur in conjunction with conventional process variation. In extreme ultraviolet lithography (EUVL) systems photon shot noise play a much larger role in image process development than in DUV processes. This is due to a lower photon count which also increases the stochastic variation of all the processes which occur after photon absorption. This causes the printed edges of features across a chip to move away from the mean edge locations with some probability that needs to be accounted for to ensure robust manufacturing.

Modern IC designs may fail if even 1 feature in 100M+ (7σ) is not patterned correctly on a layer. Therefore, it is essential to EUVL patterning to detect and fix very rarely occurring (e.g., high sigma) hotspots across the full chip. Full chip hotspot detection and repair requires the use of fast modeling methods and for EUVL these models must incorporate both stochastic and systematic effects in the process window. It is well-established in lithographic literature that the CD distribution deviates from a normal distribution for very-rare events beyond 3σ. The probability of failure due to stochastic variation in the lithography process is not governed by the stochastics of any one physical or chemical process. For example, a 7σ CD event is very unlikely to be solely caused by a 7σ event from the photon distribution alone. Instead, the final process must be understood as being dependent upon multiple stochastic events and conventional process variations that jointly result in the observed final distribution of edge positions. There will also be multiple probabilistic pathways that result in the same rare event. It is essential to EUVL process development to be able to accurately predict and correct these very rarely occurring events.

A significant problem with building a model to predict high sigma (e.g., 7+ sigma) patterning failures is in gathering the reference experimental data which can show which pattern failures do occur but only with very small probability in a chip. Collecting 100M+ experimental datapoints is not a practical option. This presentation will examine ways in which a far smaller set of experimental datapoints can be used to train fast full-chip simulation model forms to predict and compensate for very rare EUVL patterning hotspots which occur due to a combination of systematic and stochastic variations. These model forms have previously been shown to be compatible with downstream correction tools (e.g. SMO, OPC, and/or ILT). Moreover, they have been shown to be able to predict and correct stochastic variation at a full-chip scale in realistic mask designs.

Presenting Author

Zac received his B.S, M.E, degrees in Microelectronic Engineering and his Ph.D. in Microsystems Engineering from the Rochester Institute of Technology where he studied under Dr. Bruce Smith. He has worked at Micron Technologies, TrueSense Imaging, and is currently employed as an Senior Application Engineer at Synopsys, Inc. He is author or co-author of >30 papers, including peer-reviewed articles and conference proceedings. His main research interests are EUV optics and stochastic variation in lithographic processes.

P14

Materials Perspectives for EUV Pellicle Solutions (Invited)

Seong Ju Wi[1], Dongwook Kim[2], Kyeongjae Cho[2] and Jinho Ahn[1]

[1]*Division of Materials Science and Engineering*
EUV-IUCC (Industry University Collaboration Center)
Hanyang University, Seoul, 04763, Republic of Korea

[2]*Department of Materials Science and Engineering,*
University of Texas at Dallas, Richardson, TX 75080, USA

As the device manufacturers adopt EUV lithography in their production line, the control of process yield and throughput has become an important issue for the profit maximization. One of the key components which needs further improvements is the pellicle. A higher EUV transmittance (>90%) is required to guarantee a higher throughput. Due to the continuous demand on the source power upgrade, however, the thermal load on the pellicle will continue to increase even with a high EUV transmittance. IR emission is the major cooling mechanism of EUV pellicle due to membrane structure in a high vacuum environment. For this point of view, we tried to find parameters affecting thermal stability/reliability of the pellicle membrane. Experimentally we observed that IR emissivity shows linear dependency on the resistivity, which can be increased by grain boundary scattering. And the particle contamination on the pellicle surface induces localized thermal gradient (slower heating and cooling due to a higher heat capacitance of the particle compared to the pellicle membrane) can cause degraded reliability during repeated EUV scanning. Our study through thermo-mechanical modeling and empirical observation will be introduced during the presentation.

Presenting Author

Jinho Ahn received his B.S. and M.S. degrees from Seoul National University, and Ph.D. degree from the University of Texas at Austin all in Materials Science and Engineering. He worked for Microelectronics Research Laboratory at NEC, Tsukuba, Japan, and joined Hanyang University in 1995 as a professor of Materials Science and Engineering. He worked as a Director of Nano and Convergence Technology at National Research Foundation of Korea, and the Vice President of Academic Research at Hanyang University. Currently, he is the Director of EUV-IUCC, which is funded by the member companies and partially supported by the Korean government.

P15

Development of Advanced Blank Defect Avoidance Technique using Actinic Review System (Invited)

Dong Gun Lee and Byung Gook Kim

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

With EUV lithography being applied to mass production of devices, blank supply for EUV mask production is tight. Furthermore, securing an EUV blank with no defect is a significant challenge in terms of cost and quantity. Therefore, applying a blank mask with as many defects as possible to EUV mask production can bring many economic benefits. For this reason, the blank defect avoidance technology [1], which shifts the pattern so that the printed defect is minimized by using the position information of the blank defect and design of the mask pattern in advance, is generally applied.

ESOL has developed an actinic defect review system called SREM [2] and is trying to apply it to several EUV mask manufacturing processes. One of them is to improve the efficiency of blank defect avoidance technique by reviewing the blank defect that has been inspected by actinic blank inspection system. This addition of actinic review process can improve the consistency of the algorithm for determining whether the transferability of defects in a specific pattern by providing the same aerial image as the EUV scanner for blank defects, along with accurate defect position information. Through this presentation, we will also introduce phase measurement technology, an additional function of SREM that can be automatically switched from one tool.

[1] Jihoon Na, Donggun Lee, Changhwan Do, Hong-seok Sim, Jung-Hwan Lee, Jungyoup Kim, Hwan-Seok Seo, Heebom Kim, and Chan Uk Jeon, "Application of actinic mask review system for the preparation of HVM EUV lithography with defect free mask," BACUS Newsletter 33, Issue7 (2017).
[2] D. G. Lee, "Actinic Tools using Coherent EUV Source for High Volume Manufacturing," EUVL Workshop (2020).

Presenting Author

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

P16

Evaluation Results of the Rapid Probe Microscope, RPM, to Address EUV Mask 3D Metrology Requirements

M. Tedaldi[a], E. Gallagher[b], A. Frommhold[b], L. Feng[a], A.D.L. Humphris[a], J. Goulden[a]

[a]*Infinitesima Ltd., Hitching Court, Abingdon OX14 1RG UK*
[b]*IMEC, 3001 Leuven, Belgium*

EUV lithography at 0.33 NA is entering high volume manufacturing. In parallel, development activities are underway for EUV lithographic scanners with an NA of 0.55, targeting resolution down to 8nm and extending Moore's law into the next decade [1].
The mask is a critical part of the EUV imaging performance. The shorter wavelength and increased angles of illumination associated with high NA imaging will enhance sensitivity to mask surface roughness and variations in the mask absorber height. Additionally, low-error OPC models require information on the mask absorber sidewall angles and profile of different features. Finally, mask defect review can benefit from a complete profile and roughness assessment before and after repairs.

The mask CD SEM is the tool of choice for 2D mask metrology but cannot provide accurate data on the absorber height, sidewall angle or surface roughness. The Rapid Probe Microscope (RPM) [2] is introduced as a solution for mask 3D metrology. The unique technology of the RPM enables accurate 3D imaging in seconds, with a height measurement capability of 0.5nm 3 sigma.

In this paper, several application cases will be presented to demonstrate the performance of the RPM for mask metrology, examples of defect scans are shown in Figure 1 and 2. Other potential use cases will also be explored, such as the surface roughness of the multilayer mirror and the absorber layer and absorber height measurement.

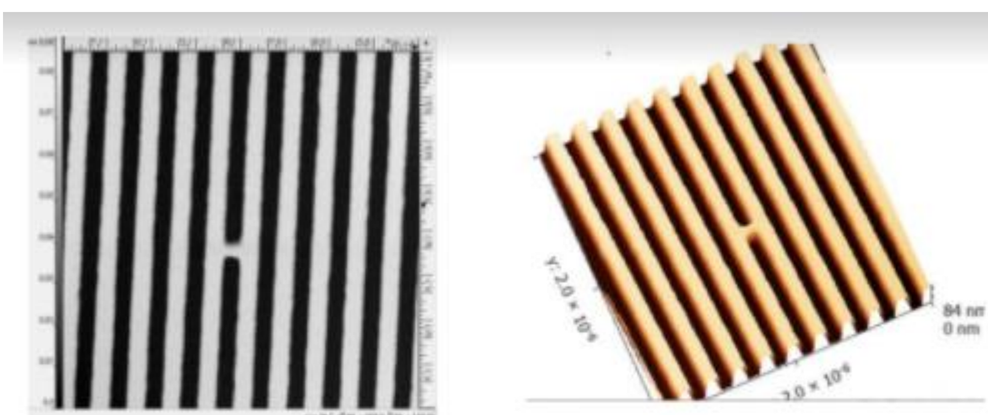


Figure 1. Example RPM image of a programmed mask defect. Field of view is 2um. Absorber depth 70nm

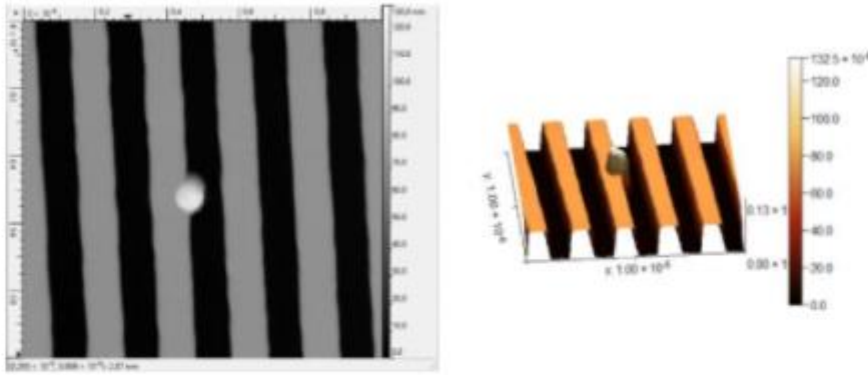


Figure 2. RPM image of contamination at the edge of the absorber. Contamination height approx. 55nm

[1] Jan Van Schoot, Sjoerd Lok, Eelco van Setten, Ruben Maas, Kars Troost, Rudy Peeters, Jo Finders, Judon Stoeldraijer, Jos Benschop, Paul Graeupner, Peter Kuerz, and Winfried Kaiser "High-NA EUV lithography exposure tool: advantages and program progress", Proc. SPIE 11517
[2] Humphris et. al., 'Probe microscopy for metrology of next generation devices' Proc. SPIE 9778 Metrology, Inspection, and Process Control for Microlithography. 2016

Presenting Author

Matthew Tedaldi has been working on advanced Scanning Probe Microscopy technologies for over 10 years. His career began in the National Physical Laboratory, the UK's National Metrology Institute, developing the Metrological AFM to deliver traceable sub nanometre 3D measurements. Since joining Infinitesima in 2016, he has focused on the application and implementation of Infinitesima's unique Rapid Probe Microscopy platform. As a Senior R&D Engineer his role is mostly dedicated to delivering quantifiable measurements in metrology and inspection in the semi-conductor industry.

P17

Measuring In-pattern EUV Phase Deviations with Linearized Scatterometry

Stuart Sherwin[a], Ryan Miyakawa [b], Isvar Cordova[b], Markus Benk[b], Laura Waller[a], Andrew Neureuther[a], Patrick Naulleau[b]

[a]: UC Berkeley, Dept. of Electrical Engineering and Computer Science
[b]: Lawrence Berkeley National Lab, Center for X-Ray Optics

With the coming introduction of new EUV absorbers, there is an increasing need for actinic phase metrology. One promising approach with demonstrated picometer sensitivity uses reflectometry to determine the phase shift between the Fresnel reflection coefficients of absorber and multilayer. One deficiency of this approach however is that the measurement can only be carried out on a blank area of the photomask, and therefore could be blind to in-pattern phase shifts that arise during mask fabrication or over the course of high-volume manufacturing. Overcoming this hurdle requires an actinic measurement of light scattered from a patterned region of the mask, where 3D scattering effects create substantial computational difficulties relative to the Fresnel coefficient calculation used in reflectometry. Here we propose a simplified solution for inferring deviations in these in-pattern phase shifts by linearizing the relationship between scattered intensity and pattern phase. Our proposed method requires measuring the scattered intensity from a periodic target on the mask, computing the difference from a pre-defined nominal signal, and taking a weighted sum of the deviation signal to estimate the phase. Both the nominal signal and the weights are determined by rigorous electromagnetic simulation of a nominal mask architecture as well as perturbations of geometric parameters.

Presenting Author

Stuart Sherwin received his Bachelor's in Physics and Applied Mathematics from UC Berkeley in 2013. Following an interlude at KLA-Tencor in the Reflective Electron Beam Lithography and 5D-Process Control teams, in 2016 he returned to UC Berkeley once again to pursue a PhD in Electrical Engineering and Computer Science. Under the direction of Laura Waller, Andy Neureuther, and Patrick Naulleau, his main research focuses are Computational Imaging and EUV Lithography.

P18

EUV Phase-Sensitive Imaging Reflectometer

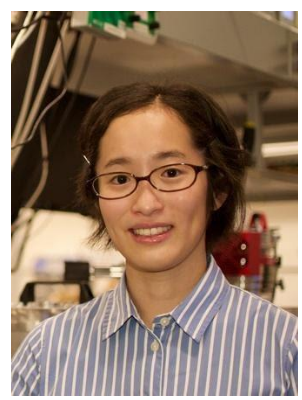
Yuka Esashi

STROBE Science and Technology Center, JILA, University of Colorado Boulder

Adoption of EUV lithography demands a parallel advance in metrology techniques with high resolution and fidelity, in particular for actinic characterization of EUV masks. We present a table-top phase-sensitive imaging reflectometer, which combines coherent diffractive imaging with reflectometry to generate phase- and amplitude-reflectivity maps of a sample at many incidence angles non-destructively. From the resulting angle-dependent reflectivity map, the 3D composition of the sample can be solved in a spatially- and depth-resolved manner. The microscope is illuminated by coherent EUV high harmonic beams, with selectable wavelengths between 30 and 13.5 nm, allowing us to harness the high spatial resolution and chemical specificity inherent to EUV light. Coherent diffractive imaging measures the phase shift upon reflection in addition to the absolute reflectance, giving the technique an enhanced sensitivity to material composition and surface topography, as well as a unique ability to measure the phase of EUV masks with precision approaching 0.2 degrees. We have demonstrated this technique on a lithography test sample from imec, where we were able to solve for various parameters of interest to the industry, including layer thicknesses, structure heights, and dopant levels, which were verified using correlative metrology [1].

[1] Tanksalvala et al., "Nondestructive, high-resolution, chemically specific 3D nanostructure characterization using phase-sensitive EUV imaging reflectometry", Science Advances, 7, 5, eabd9667 (2021).

Presenting Author



Esashi is pursuing her PhD in physics at the University of Colorado Boulder in the Kapteyn–Murnane group. She is co-lead of the team implementing the first table-top, ptychographic phase-sensitive imaging reflectometer with EUV light, that can nondestructively image depth-dependent composition of nanofabricated samples. Esashi received her BA in Physics from Reed College in 2017, and her MS in Physics from the University of Colorado Boulder in 2019.

P19

EUV Mask imaging Performance Enhancement through Aerial Image Optimization

Deukgyu Kim[1, 3], Dongmin Jeong[2, 3], Yunsoo Kim[2, 3], Minsun Cho[1, 3], and Jinho Ahn[1, 2, 3]

[1]Division of Nanoscale Semiconductor Engineering
[2]Division of Materials Science and Engineering
[3]EUV-IUCC (Industry University Collaboration Center), Hanyang University, Seoul, 04763, Republic of Korea

Extreme ultraviolet (EUV) lithography is in High volume manufacturing (HVM) for 7 nm node and will continue expanding to future 5 nm node and beyond. But since there are severe mask 3D effects such as non-telecentricity and best focus shift, the EUV mask still struggles with mask contrast degradation.

In this work, we studied the optical property of the EUV absorber materials for the image contrast optimization. We investigated the effects of phase and amplitude difference between the 0th and 1st diffraction orders on the imaging performance in the range of low-n ($0.87 \leq n \leq 0.91$) EUV mask absorbers. The simulation was performed for 14 nm half-pitch line and space patterns with a leaf dipole off-axis illumination condition using KLA Prolith 2020a simulation tool. We found that the image split, which means the difference in distance between the aerial images formed from each pole, was reduced by using the optimum phase difference between the 0^{th} and 1^{st} diffraction orders. In the case of 14 nm HP L/S patterns, the optimum phase difference is 150 degrees. In addition, this result becomes more clearly as the amplitude difference between the two diffraction orders decreases.

As a result, it is possible to maximize mask image performance by optimizing the phase in the low-n absorber range, where the amplitude difference between the two diffraction order were minimized.

This research was supported by National R&D Program through the National Research Foundation of Korea(NRF) funded by Ministry of Science and ICT(NRF-2020M3H4A3081881)

Presenting Author

Deukgyu Kim received his B.S. degree from Hanyang University in materials science and engineering, and he is studying EUV mask for next generation EUV lithography at Hanyang University as a master course of nanoscale semiconductor engineering.

P20

Study on the degradation of EUV transmittance for EUV pellicle during exposure process

Chang Soo Kim[1,4], Yong Ju Jang[2,4], Seong Ju Wi[3,4], Ha Neul Kim[3,4], and Jinho Ahn[1,2,3,4]

[1]*Department of convergence nanoscience*
[2]*Division of Nanoscale Semiconductor Engineering*
[3]*Division of Materials Science and Engineering*
[4]*EUV-IUCC (Industry University Collaboration Center), Hanyang University, Seoul, 04763, Republic of Korea*

The oxidation may occur as the temperature of extreme ultraviolet (EUV) pellicle increases during exposure process, which causes a change in optical properties of the thin film. In this paper, the cause of the decrease in EUV transmittance of pellicle during the exposure process was analyzed, and a guideline for thin film deposition was proposed to minimize the decrease in EUV transmittance.

Ru/SiN_x double-layer membrane was fabricated. In order to analyze the oxidation properties depending on microstructure, the Ru layer was deposited at various working pressure such as 0.5, 1, 2 mTorr. The pellicle was heated through UV irradiation under emulating EUV exposure condition. The composition and microstructure of Ru and SiN_x were analyzed using X-ray photoelectron spectroscopy (XPS) and transmission electron microscopy (TEM). The EUV transmittance was measured by EUV coherent scattering microscope (CSM).

As a result, the EUV transmittance of Ru/SiN_x pellicle deposited at 0.5, 1, and 2 mTorr were measured as 80.5%, 80.1%, and 79.1%, and it was reduced to 79.2%, 77.9%, and 76.3% by heating. It was confirmed that as the working pressure increased, the void network in the Ru layer increased and the SiN_x layer was oxidized by heating. From these results, the effect of oxygen diffusivity changes due to void network formation in Ru layer on SiN_x oxidation was qualitatively investigated. In addition, based on the structure zone model (SZM), a thin film deposition guideline that can minimize the decrease in EUV transmittance of pellicle was suggested as fewer voids are formed.

Acknowledgments
This research was supported partly by Fine Semitech Corp. (FST) and Nano Material Technology Development Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and Information Communication Technology (ICT) (No. 2019K1A3A1A14067316).

Presenting Author

Chang Soo Kim received his B.S. degree from Soongsil University in physics, and he is studying EUV pellicle for next generation EUV lithography at Hanyang University as a master course of convergence nanoscience.

P21

Synthesis of Organic-Inorganic Hybrid EUV Resists by Atomic Layer Deposition (Invited)

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

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

Hybrid photoresists containing inorganic elements offer high EUV absorption and etch resistance. Optimizing resist exposure and patterning characteristics in hybrid resists requires a facile control of the type and composition of incorporated inorganic elements, a non-trivial task for the typical chemical synthesis. In this talk, I will discuss our recent progress on synthesizing hybrid resists based on atomic layer deposition (ALD) and preliminary EUV and low-energy electron exposure studies. Two distinctive approaches will be presented, infiltration synthesis [1] and molecular ALD (MALD) [2]. The former utilizes an infiltration of vapor-phase inorganic precursors into organic resists and the latter a recursive layering of organic and inorganic molecular monolayers. Given facile implementablility and ex-situ control of resist characteristics, the ALD-based hybrid resist synthesis has a potential for enabling high-performance EUV resists.

[1] N. Tiwale et al., *Proc. SPIE* **11612**, Advances in Patterning Materials and Processes XXXVIII, 116120A (2021)
[2] J. Huang et al., *J. Mater. Chem. C.* **4**, 2382 (2016)

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 awards include BNL Spotlight Awards (2018, 2011) and Goldhaber Distinguished Fellowship (2007).

P22

Investigations of EUVL Photoresists at the Advanced Light Source (Invited)

Luke Long,[1] Terry McAfee,[1] Patrick Naulleau,[1] and Slavomír Nemšák[2]

[1]Center for X-ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA 94720
[2]Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

At present, the success in the continuing miniaturization in the semiconductor industry depends mostly on novel photolithographic techniques. In this work, we present the experimental efforts focused on EUVL photoresists that are taking place at the Advanced Light Source. The EUV radiation together with generated photoelectrons induce structural and physio-chemical processes of the resists resulting in changes of their optical properties.

X-ray photoemission spectroscopy (XPS) is a non-destructive technique that provides information on the chemical and elemental composition of the photoresits as well as on any present contaminants. In addition, when combined with standing-wave (SW) excitation, it can provide non-destructive chemical and physical information of buried interfaces as well as chemical and structural depth profile information with a few Angstrom resolution.

Another X-ray technique, Resonant Soft X-ray Scattering (RSoXS), probes the size scale and distribution of aggregates within a photoresist by utilizing enhanced contrast provided by chemical-bond specific contrast. RSoXS is typically limited to investigating features 1 nm or larger in size, but can probe sub-nm features using a line pattern approach.

G. Conti et al., Extreme Ultraviolet Lithography 115170I (2020); https://doi.org/10.1117/12.2575463.

Presenting Author

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

P23

Exploring Backbone Ionization in EUV Resists Using Computational Chemistry

Jonathan H. Ma

CXRO, Lawrence Berkeley National Laboratory, Berkeley, CA-94720, USA
Dept. of Physics, UC Berkeley, 366 LeConte Hall, Berkeley CA 94720, USA

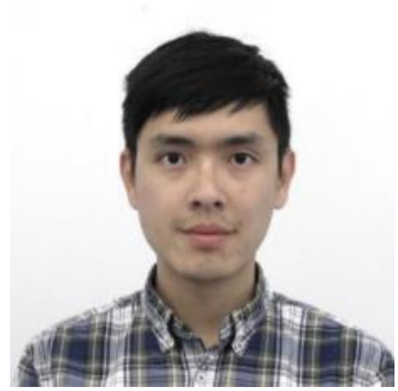
The introduction of EUV lithography has triggered a new wave of material exploration. There are a few challenges, including novel radiation chemistry and the Resolution-LER-Sensitivity (RLS) trade-off. Innovative resist chemistry can lead to higher quantum efficiency, which can help defeat the RLS trade-off. Mechanistic investigations are therefore in the spotlight again.

Each EUV photon creates a cascade of secondary electrons which also leaves behind multiple ionized resist molecules. On the one hand, the role of secondary electrons in chemically amplified resists (CAR) has been extensively studied—they are shown to play a major role in photo acid generator (PAG) activation. On the other, ionization chemistry could provide extra leverage for dissolution chemistry.

Ionized species are short-lived and very unstable. While experimental studies exist, they are made difficult by the transient nature of the reactive ionic species. Experimental efforts can therefore be complemented by quantum chemistry computations, which provide a preliminary understanding of ionization chemistry at a higher throughput, making it a useful tool for identifying promising candidate materials.

We seek to understand the utility of this tool by studying relatively well-known systems such as PMMA. Afterwards, we would proceed to investigate more novel idea such as the inclusion of nitrogen into the polymer backbone. The inclusion of nitrogen can be used to tune the ionization energy of the polymer. Its presence could however facilitate alternative ionization chemistry. Quantum chemistry would therefore be a viable tool to understand the interplay between the two.

Presenting Author



Jonathan H Ma is a graduate student from UC Berkeley. Working with Dr. Patrick Naulleau and Dr. Andrew Neureuther at the Center for X-ray Optics, his work focuses on understanding the novel radiation chemistry of EUV resists in various EUV material systems with both experiments and quantum chemistry computations.

P24

EUV Resist Development Program at NewSUBARU (Invited)

Takeo Watanabe, Shinji Yamakawa, Tetsuo Harada

University of Hyogo

Extreme ultraviolet lithography is used in high volume manufacturing of 5-nm logic device for the smart phones in 2020. IT technologies requires the semiconductor device which has high operation frequency, low power consumption, and low production costs. Thus, more advanced lithography is required.

NewSUBARU synchrotron light facility at University of Hyogo is the largest synchrotron facility which is operated by the university in Japan. The main mission of this facility is strong contribution to resolve the technology issues by the synchrotron industrial applications.

In the development of EUV lithographic technology, the fundamental R&D has been carried since 2000. The novel EUV resist development program and technologies will be introduced.

Furthermore, our own electron beam injector is going to install for NewSUBARU synchrotron electron beam storage ring. This linear accelerator (linac) is c-band accelerator which has half length of the previous linac, and can accelerate the electron beam to 1.0 GeV.

Presenting Author

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

P25

A Stochastic Resist Model Based Comparison of 0.33NA and 0.55NA Lithography

Ruben Maas, Gijsbert Rispens, Eelco van Setten, John McNamara, Jan van Schoot

ASML, Veldhoven, The Netherlands

In this work, we introduce a 3D stochastic resist model developed to evaluate lithography performance. We use the model to determine what dose-to-size, pattern variability and stochastic defectivity to expect for several use-cases. Furthermore, the model is applied to quantify the impact of resist properties such as film thickness, absorptivity, and blur on pattern variability and defectivity. One key finding is that taking into account the 3D nature of patterns is essential to predict stochastic defectivity. Furthermore, it is found that local chemical variability within the resist has a significant contribution to the total pattern variability.

Finally a model based comparison of 0.33NA and 0.55NA scanner performance is made in terms of stochastic defectivity. A hexagonal pitch 28 nm contact hole pattern is studied as a test use-case. This pattern can be printed with 0.33NA in a double exposure flow, or with a single exposure using a 0.55NA scanner. The higher optical contrast of 0.55NA leads to a larger defect-based exposure latitude, but comes at the cost of a limited defect-based depth-of-focus. This work shows the need for careful pupil optimization to balance the peak normalized image log slope with the depth-of-focus.

Presenting Author

Ruben Maas studied physics at Utrecht University and received his PhD in nanophotonics from the University of Amsterdam in 2015, working on the fabrication and characterization of optical metamaterials. Since then, he has joined the Research department of ASML and works on stochastics in EUV lithography and SEM metrology.

P26

A Decade of Progress in EUV resists (Invited)

Y. Ekinci

Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

EUV lithography has become the leading lithography technique in semiconductor manufacturing. Development of effective EUV resists was one of the key achievements that enabled this success. Towards high-NA EUVL photoresists with better resolution and line-edge roughness are needed. In this talk, I will review the advancements in EUV resists and also the current status. I will also talk about the importance of metrology in assessment of resist performance and about our efforts to improve this.

Presenting Author

Yasin Ekinci is head of the Laboratory of Micro and Nanotechnology at Paul Scherrer Institute, Switzerland. He obtained his PhD in Max-Planck Institute for Dynamics and Self-Organization, Göttingen, Germany in 2003. In 2004, he joined Paul Scherrer Institute as a postdoctoral researcher. Between 2006 and 2012 he worked as a postdoctoral researcher and subsequently as a senior scientist and a lecturer in Department of Materials at ETH Zürich. He is at PSI since 2009 working on various topics of nanoscience and technology, including EUV lithography, resist materials, lensless imaging, plasmonics, semiconductor nanostructures, and nanofluidics. He is author/co-author of more than 220 papers and 7 patent applications. He is a fellow of SPIE.

P27

EUV Lithography using Multi-Trigger Resist (Invited)

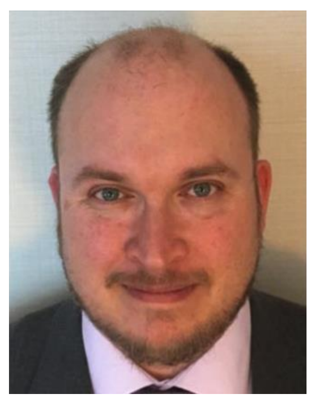
C. Popescu[a], G. O'Callaghan[a], A. McClelland[a], J. Roth[b], T Lada[b], T Kudo[c], M Moinpour[c], Y Cao[c], A.P.G. Robinson[a,b]

[a]*Irresistible Materials, Birmingham Research Park, Birmingham, UK*
[b]*Nano-C, 33 Southwest Park, Westwood, MA, USA.*
[c] *EMD Performance Materials Corp, Merck, USA*

The development of novel EUV resists is widely agreed to be one of the highest priority challenges for the deployment of high-NA EUV lithography. One potential approach is the multi-trigger concept wherein a reaction will only occur when multiple elements of the resist are initiated concurrently and in close spatial proximity. At the centre of exposed features, where the exposure dose is sufficient the resist reaction is thus catalytic as in a CAR, but at the edge of the features the reaction is second-order in nature, and thus the chemical gradient is increased. In effect the resist features an intrinsic, inversely dose dependent, quenching of the catalysis, enhancing the chemical contrast and thus resolution, and reducing roughness.

The multi-trigger material consists of a novel MTR molecule and a crosslinker, which represent the resist matrix, together with a photoacid generator (PAG). Research is continuing to upgrade this resist, in particular focusing on improving resist opacity and crosslinking density. A new high-Z crosslinker molecule has been synthesized and formulated in the MTR resist. We report results obtained using this new MTR system containing this cross-linker, with a variety of process conditions and formulation variations. Furthermore, we have also investigated increasing the activation energy of the self-quenching aspect of the MTR system.

Presenting Author



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

P28

Exploration of Thin Films for High NA EUV Lithography

Joren Severi

KU Leuven, Celestijnenlaan 200F, B-3001, Leuven, Belgium
Imec, Kapeldreef 75, B-3001, Leuven, Belgium

The current advancement of EUV lithography (EUVL) is heavily based on the advancement to the so-called high NA EUVL. At the same time, the film thickness that is used for resist patterning must be reduced due to the expected reduced Depth-of-Focus (DoF) because of the higher NA, as well as to prevent pattern collapse due to high aspect ratios for smaller pitches. Reducing the film thickness leads to an expected more dominant interaction of resist and underlayer which may lead to changes in material characteristics that could affect the resist patterning performance, as well as metrology issues. To this end an exploration of thin films was started at imec of which some results will be presented during this talk.

Presenting Author

Joren Severi has received his Master of Chemistry degree from KU Leuven in 2018, after which he started a PhD in Chemistry in the Exploratory Patterning Materials (EPM) group at imec. The main topic of the thesis is ultra-thin film characterization for high NA EUV lithography. The outcome of the thesis should provide insight in both potential material changes, changes in resist patterning performance, and ultimately design rules for resists going to these ultra-thin films.

P29

Experimental Characterization of Model Polymers (Invited)

Oleg Kostko,[1,2] Terry McAfee,[2] Jonathan Ma,[2,3] Patrick Naulleau[2]

[1]*Chemical Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
[2]*Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
[3]*Department of Physics, University of California, Berkeley, CA, USA*

The absorption of an EUV photon by a thin film resist leads to emission of primary and secondary electrons. The electrons may travel up to tens of nanometers before losing their kinetic energy via collisions which initiate chemical reactions. The "blur" of an aerial image is directly related to the distance that electrons are able to travel in the resist. Thus, identifying how to measure and influence the absorption of EUV photons, emission of electrons, and distance traveled by the secondary electrons is extremely beneficial to the resist community.

In this work, we utilize several model polymer materials to experimentally investigate the impact of specific chemical groups on three critical resist properties: EUV absorption, electron emission, and the electron attenuation length (EAL). EUV absorption dictates the efficiency of the film to absorb photons. Total electron yield (TEY) provides information on the conversion of absorbed EUV photons to electrons. The EAL corresponds to the thickness of a material required to reduce the number of emitted electrons to 1/e of the initial value. The EAL reveals the distance the electrons can travel in a resist film, which is directly related to the electron blur. We will also discuss correlations between the obtained experimental values.

Presenting Author

Oleg Kostko obtained his doctoral degree from the University of Freiburg, Germany, in 2007. 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 to the Berkeley Lab to lead an effort for developing novel soft x-ray spectroscopies on nanoscale systems. He also investigates fundamental processes in EUV induced chemistry.

P30

Recent Progress in a Dry-deposited and Dry-developed EUV Photoresist System (Invited)

Nader Shamma

Lam Research, 4650 Cushing Parkway, Fremont, CA 94538, U.S.A.

Extreme ultraviolet (EUV) lithography has been introduced into high volume manufacturing (HVM) of semiconductor ICs beginning at the 7nm node logic and is being qualified for an increasing proportion of lithography layers at 5/3nm logic and 16/14nm DRAM. A persistent challenge of the EUV scanner is to supply a high contrast image with sufficient photons to the photoresist to meet HVM productivity targets with acceptable dimensional and defectivity control. Local stochastic variability dominates the total dimension control budget and reducing that variability -by increasing the exposure dose- comes at the cost of scanner throughput.

EUV scanner power and reliability have made significant improvements over the last decade to HVM levels; however photoresists have not kept pace with the increasingly stringent technology requirements during the same period. Spin-on photoresist materials are still unable to meet the sensitivity, resolution, and defectivity targets for HVM of the most advanced technology nodes. This gap in photoresist readiness has required IC fabs to make compromises in design and cost and placed significant burden on downstream processes to compensate for limitations in the lithography pattern, providing a significant opportunity for innovation.

We discuss here our revolutionary technique to both apply photoresist and develop latent images in photoresist using dry technologies instead of the existing wet spin coating and development that have been in use for over 40 years. We will review the key advantages of dry resist processing over wet resist processing: stability, photosensitivity, environmental footprint, process window, and cost. This nascent technology has demonstrated best-in-class photoresist performance at leading edge design rules and enables a new world of innovations in EUV lithography patterning.

Presenting Author

Nader Shamma is currently serving as Technical Director at Lam Research Office of CTO. He has contributed to the development of several generations of lithographic processes for advanced semiconductor IC fabrication.

P31

EUV Resists: Pushing the Limits (Invited)

Anna Lio

Intel Corporation

Extreme Ultraviolet Lithography (EUVL) has become mainstream. Its continued success is strongly dependent on pushing EUV photoresists to their limits. We discuss status of EUV photoresist development and asks of the entire EUV ecosystem to enhance and accelerate EUV resist development.

Presenting Author

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

P32

Resist Screening with EUV Interference Lithography: From Omelet Lithography to State-of-the-art Performance Resists

T. Allenet[a], M. Vockenhuber[a], C-K Yeh[a], J. G. Santaclara[b], L. Van Lent-Protasova[b], Y. Ekinci[a]

[a] Laboratory for Micro- and Nanotechnology, Paul Scherrer Institut, 5232 Villigen-PSI, Switzerland
[b] ASML, De Run 6501, 5504 DR Veldhoven, The Netherlands

As EUV lithography becomes the new standard for electronic chip manufacturing, reaching future technology nodes with EUV remains to be a substantial field of research. Within sub-fields of interest, identifying suitable materials for higher resolution patterning stands out as a prominent challenge. As standardly used materials approach their theoretical limitations, innovative approaches to patterning are becoming more and more relevant.

In this work we investigate the relevance of PSI's EUV-Interference Lithography exposure-tool for the screening of materials to be used in future High-NA scanners. We present lithography results with an unconventional material to underline the potential of EUV patterning as a photoelectron induced interaction as well as EUV-IL tool versatility. An egg white albumin protein-cluster is used as a photosensitive material to obtain sub-100 nm patterns with EUV lithography. Moving from these novel EUV lithography results we show recent high-resolution highlights obtained towards the patterning of sub-10 nm features.

Presenting Author

P33

Large-area Nanopatterning and Industrial-resist Testing with an in-lab EUV Dual Beamline

Bernhard Lüttgenau[a,b], Sascha Brose[a,b], Serhiy Danylyuk[c], Jochen Stollenwerk[a,b,c], Peter Loosen[a,b,c]

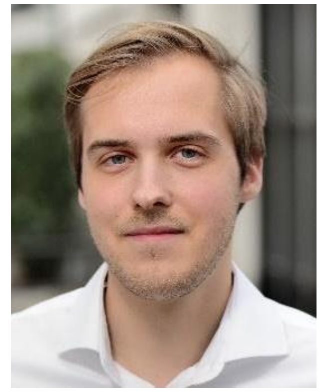
[a] RWTH Aachen University, Chair for Technology of Optical Systems, Aachen, 52074, Germany
[b] JARA – Fundamentals of Future Information Technology, Jülich, 52428, Germany
c Fraunhofer Institute for Laser Technology, Aachen, 52074, Germany

In this contribution the authors present advanced nanopatterning for scientific and industrial applications with an in-lab EUV Dual Beamline. The EUV Dual Beamline is a versatile exposure tool equipped with a compact discharge-produced plasma (DPP) EUV source and can be operated either at an exposure wavelength of 10.9 nm or 13.5 nm, depending on the application.

By operating the source with an Ar/Xe gas mixture, a narrow-band spectrum with a main wavelength of 10.9 nm is created without the need of spectral filtering. The resulting intensity of up to 2 mW/cm² in wafer plane allows large area patterning with highest throughput of several mm²/min. Qualification of industrial photoresists regarding sensitivity, contrast and resolution is enabled by operating the DPP source with pure Xe. The resulting broadband emission is spectrally filtered to 13.5 nm in-band radiation by 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 carefully 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 with the realized in-lab EUV Dual Beamline.

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.

P34

Vapor-phase Infiltration for High-sensitivity Hybrid Nanolithography Resists Synthesis

Nikhil Tiwale[1], Ashwanth Subramanian[2], Kim Kisslinger[1], Ming Lu[1], Aaron Stein[1], Jiyoung Kim[3], and Chang-Yong Nam[1,2]

[1]*Center for Functional Nanomaterials, Brookhaven National Laboratory, Upton, NY 11973, USA*
[2]*Department of Materials Science & Chemical Engineering, Stony Brook University, Stony Brook, NY 11794, USA*
[3]*Department of Materials Science and Engineering, University of Texas at Dallas, Richardson, TX 75080*

Prospects of increased EUV absorption & robustness for dry etching are proving hybrid resists effective in addressing rigorous EUVL process requirements for high volume manufacturing. However, complexity of syntheses continues to remain hurdle in compositional & performance control. Our novel vapor-phase infiltration approach enables versatile ex-situ controllability over these key parameters, as demonstrated by our model PMMA-AlO_x hybrid.[1,2] We expand our material portfolio to high sensitivity organic resists and high EUV absorbing inorganic moieties. We explore combination of hybrid resist composition and evolution of their resist sensitivity, contrast with solvent-base combinational formulation of developer chemistry for residue free high-resolution patterning. Along with studying these hybrid resists for EBL, we also report preliminary results outlining their use for EUVL,[3] which could potentially pave the way for high throughput patterning.

References - [1] N. Tiwale, et al., J. Mater. Chem. C **7**, 8803 (2019)
[2] N. Tiwale, et al., Proc. SPIE **11326**, Advances in Patterning Materials and Processes XXXVII, 113260J (2020)
[3] N. Tiwale, et al., Proc. SPIE **11612**, Advances in Patterning Materials and Processes XXXVIII, 116120A (2021)

Presenting Author

Nikhil Tiwale is a Research Associate at CFN/BNL Electronic Nanomaterials group, 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 making ZnO nanoFETs and gas sensors, under the supervision of Prof. Sir Mark Welland. Before joining BNL, he briefly worked at a startup, Adaptix, as silicon process engineer.

P35

Photochemical Reaction Study of Metal Introduced E-beam Resists Using Vapor-Phase Infiltration

Su Min Hwang[1], Aditya Raja Gummadelly[1], Dan N. Le[1], Yong Chan Jung,[1] Jinho Ahn[2], Chang-Yong Nam[3] Jiyoung Kim[1]*

[1]*The University of Texas at Dallas, Richardson, Texas 75080, USA.*
[2]*Hanyang University, Seoul 04763, Korea.*
[3]*Brookhaven National Laboratory, Upton, New York 11973, USA*

Significant efforts have been dedicated to the development of inorganic-organic hybrid materials as EUV resist to achieve stringent requirements, such as high EUV sensitivity, small line edge roughness, high patterning resolution, etch resistance, and pattern collapse. Recently, vapor-phase infiltration (VPI) of metal source into existing resists using ALD process can be a promising technique. Compared to hybrid nanoparticle-containing resists, VPI process is expected to provide uniform distribution with an ease of controlling metal concentration, improving EUV absorption and material properties.

In this study, we have infiltrated Hf and Al sources into conventional PMMA and HSQ e-beam resists, respectively, and photochemical reactivity of inorganic organic hybrid resists was investigated using electron flood gun. Under 100 eV exposure, similar to incident photon energy of EUV, both Hf-PMMA and Al-HSQ resists show a relatively higher electron absorption compared to pristine resists, increasing positive and negative features, respectively. This suggests that VPI process can be a potential EUVL application. The detailed photochemical reaction of Hf-PMMA and Al-HSQ during electron exposure were investigated using an *in-situ* FTIR system, equipped with electron gun capability.

This work is funded by Brain Pool Program through National Research Foundation by the Ministry of Science and ICT in Korea (No. 2019H1D3A2A01101691).

Presenting Author

Su Min Hwang received his B.S. and M.S. degree in the Department of Chemical Engineering from Inha University, Korea, in 2014 and 2016, respectively. He joined the Ph.D. program in spring 2017 under the supervision of Dr. Jiyoung Kim.

P36

High-speed AFM for Full-strength, Spatially-resolved, In-situ Dissolution Rate Monitoring

Luke Long[1,2], Jiajun Chen[2], Andrew Neureuther[1,2], Patrick Naulleau[2], and Paul Ashby[2]

1. University of California at Berkeley 2. Lawrence Berkeley National Lab

Despite being a crucial part of the lithography process, measurement of photoresist dissolution at industrially relevant spatial and temporal has remained elusive. Current resist metrology ignores either the temporal component of the dissolution process by measuring the final developed structure, or the spatial component as is done in most dissolution rate monitoring techniques. These methods thus shed little insight into the interplay between the dissolution process and pattern roughness/ failure. To that end, we present our work on the use of high-speed atomic force microscopy (AFM), using full-strength developer as means to performing in-situ dissolution rate monitoring. As opposed to pioneering work using AFM to monitor the dissolution process, our technique incorporates the use of a specially-designed flow cell that provides precise control of the time at which developer is introduced to the photoresist material, as well as delivery of nearly full-strength developer in fractions of a second. Our system thus offers the ability to probe the spatially-dependent nature of the dissolution process, providing insight into dissolution rate gradients, material swelling, and other lithographically relevant phenomena. In doing so, we provide another technique to aid in the design and study of photoresist materials for future lithographic nodes.

Presenting Author

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

P37

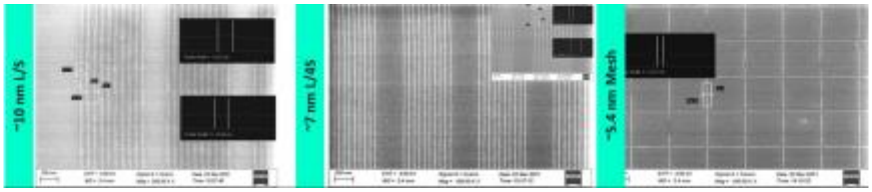
Cyclotrimeric Organotin Based Single-Component Resist for Patterning at Single-Nanometer Regime Using Electron-Beam Lithography

Santu Nandi[1], Lalit Khillare[1], Mohamad G. Moinuddin[2], Satinder K. Sharma[2], Subrata Ghosh[1]*, Kenneth. E. Gonsalves[1]*

Indian Institute of Technology Mandi
[1]School of Basic Sciences [2]School of Electrical and Computer Engineering Mandi HP 175005, India

Shrinking of transistor size is paramount in order to meet the demand of semiconductor market particularly for technologically advanced electronic devices. In this regard, nanolithography is playing a crucial role as a promising technology for high volume nanochip manufacturing. In recent times, modern nanoelectronics devices are enabled with Integrated circuits (IC) chips for improved performance. With the aid of extreme ultraviolet lithography (EUVL), the chip fabrication technology is approaching toward 3 nm or below nodes. Hence, this is an era of technology nodes at the single-nanometer regime. Therefore, resist materials with potential for patterning sub-10 nm features on single exposure are highly demanding, although very challenging. In recent time, resist compositions comprising of inorganic or organometallic species have attracted special attention largely due to their resolution potential at single-nanometer regime as well good etch resistance properties.

The current presentation will provide an overview of our recent results on the possibility of using organotin-based cage-like networks for sub-10 nm patterning. We have shown the potential of a cyclotrimeric organotin compound as a resist for patterning features at the single-nanometer regime. In general, the resists to be used for EUVL are initially screened using electron beam lithography (EBL) at the developmental stage. Using EBL, we have been successful in patterning ~6 nm isolated features as well as 10 nm dense features (line/space) at dose of 2.5 mC/cm^2.We believe the present resist composition may show sub-5 nm patterning potential under more optimized condition. Hence, our current focus is on significantly improving the dose, initially ebl prescreening, followed by EUV single digit nanopatterning with LER within budget.



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Presenting Author

Subrata Ghosh received his Ph.D. from the Department of Chemistry, Indian Institute of Technology Guwahati in 2006. At present, he is serving Indian Institute of Technology Mandi as Professor of Chemistry in the School of Basic Sciences. He is currently focusing on the development of organic and organic inorganic hybrid molecular and macromolecular materials for optoelectronics, semiconductor fabrication and biomolecule imaging. He focuses also on understanding the fundamental aspects of such materials at the molecular level.

P38

Progress in Metal-Organic Cluster Resists Towards the Deployment of Second Generation EUV lithography

Manvendra Chauhan[1], Subrata Ghosh[2], Satinder K. Sharma[*1], Kenneth. E. Gonsalves[2*]

[1]School of Computing & Electrical Engineering (SCEE), [2]School of Basic Sciences (SBS), Indian Institute of Technology (IIT), Mandi, MANDI-175075, (Himachal Pradesh), India

Metal organic cluster (MOC) resists have drawn significant attention for next generation extreme ultraviolet lithography (EUVL) applications due to its sub-16 nm patterning capabilities at high sensitivity [1]. Sensitivity is one of the main factors along with line edge/width roughness and etch resistance that must be in agreement for the advancement and progress of the semiconductor industries relies on EUVL production. The broad consent on this course has triggered the need of incorporation of metals with high EUV absorption coefficient or high optical density (OD) to incorporate into the resist materials [2]. High OD metal core plays a significant role to absorb and transfer the irradiated exposure beam to the attached organic functionalities and boost the internal mechanism, where organic moieties offer the possibilities of patterning by photon or charged particle based lithography. The selection of metal core with high absorbance coefficient is as crucial as the presence of weak organic ligand to increase the sensitivity of the resist [3-4]. In this context, we formulated a novel MOC resist with the Bismuth (Bi) as a metal core and weaker binding ligand, methacrylic acid (MAA) to satisfy the requirement of resolution, line edge/width roughness, and sensitivity (RLS) tradeoff as per the latest IRDS roadmap. The controlled electron-beam lithography (EBL) experiments and analysis shows the capability of Bi-MAA, MOC resist for reliable high-resolution (HR) sub-15 nm patterning at under budget e-beam dose.

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Presenting Author

Manvendra Chauhan received his B. Tech. degree in electronics and communication engineering from Invertis Institute of Engineering and Management (IIEM), Bareilly, India in 2014 and M. Tech in Digital electronics from Madan Mohan Malaviya University of Technology (MMMUT), 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.

P39

Investigation of Stochastic Effects on EUV Ready Indium Based Metal-Organic Cluster Resist

Satinder K. Sharma*[1], Manvendra Chauhan[1], Subrata Ghosh[2], Kenneth. E. Gonsalves[2*]

[1]School of Computing & Electrical Engineering (SCEE), [2]School of Basic Sciences (SBS), Indian Institute of Technology (IIT), Mandi, MANDI-175075, (Himachal Pradesh), India

Enabling the cutting-edge next-generation semiconductor technology roadmap, extreme ultraviolet lithography (EUVL) enters into its next generation high-NA lithography that require highly sensitive resist materials, processes with improved resolution and pattern roughness [1-2] to fully capture the imaging advantage of the high NA tool. Metal organic cluster resists matured into promising alternatives to the traditional EUV resists for processes with limited exposure latitudes such as High-NA EUVL and offers sub-20 nm feature size with high etch resistance [3]. The probability of stochastic defects on EUV ready resists systems increases exponentially with reduction of feature size. Photon shot noise and resist chemistry along with the various lithography processing conditions can be accountable as the cause for stochastic effects [4]. In this work, we investigate the stochastic effects on Indium (In) based MOC, In-MAA resist [5] by considering the defects such as line breaking and bridging, line edge/width roughness and pattern collapse as a function of electron/ion beam exposure to find suitable material approaches for further improvement. To improve the resist stochastic, defects are directly correlated to electron/ion beam exposure doses, which must be considered prior exposure to EUVL. The defect analysis performed on the sub 15 nm half-pitch (HP) line patterns of the In-MOC resist formulation and confirmed its capability of reducing resist-based stochastic defects and strengthen its candidature for the potential EUV resist.

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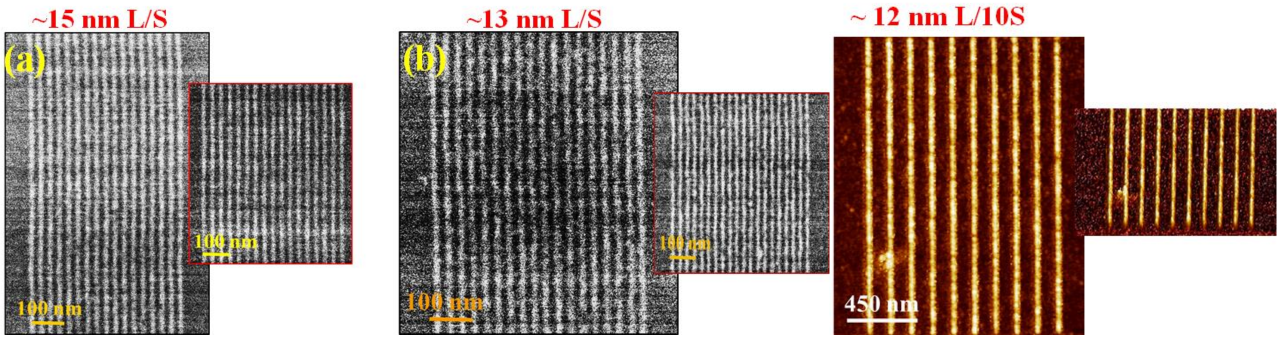

Figure 1: FESEM images of In-MAA resist patterns at ~45 μC/cm^2 EBL dose of features: (a) 15 nm L/S, and (b) AFM image of line patterns on EBL exposed In-MAA resist

Presenting Author

Satinder K. Sharma (Senior Member, IEEE) received the Master of Science in Physics (Electronic Science) from Himachal Pradesh University, Shimla, India, in 2002, and Ph.D. degree from the Department of Electronic Science, Kurukshetra University, Kurukshetra, India, in 2007. From 2007 to 2010, he was a Postdoctoral Fellow with the DST Unit on Nanoscience and Nanotechnology, Department of CHE, Indian Institute of Technology Kanpur, Kanpur, India. From 2010 to 2012, he worked as a faculty with the Electronics and Microelectronics Division, Indian Institute of Information Technology, Allahabad, India. Since 2012, he has been working as a faculty with the School of Computing and Electrical Engineering, Indian Institute of Technology Mandi, India. 2015 he worked as Visiting Faculty, Institute of Semiconductor Electronics, Stuttgart University, Germany. He published more than 90 publications in the international peer review Journals, and also presented several invited talks and research papers more than 60 international and national conferences along with submitted eight patents. His current research interests include microelectronics circuits and system, CMOS device, nano/microfabrication, advanced lithography, sensors and self-assembly.

P40

Material-specific analysis of multi-layers with XUV Coherence Tomography

Silvio Fuchs[1,2,3], Felix Wiesner[1], Martin Wünsche[1,2,3], Julius Reinhard[1,2], Johann Jakob Abel[1], Jan Nathanael[1,2], Slawomir Skruszewicz[1], Christian Rödel[1,2], Gerhard G. Paulus[1,2]

[1] Institute of Optics and Quantum Electronics, Max-Wien-Platz 1, 07743 Jena, Germany
[2] Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena, Germany
[3] Indigo Optical Systems, Jenaische Str. 7, 07747 Jena, Germany

XUV Coherence Tomography (XCT) [1, 2, 3] is a derivative of Optical Coherence Tomography (OCT) for the extreme ultraviolet and soft x-ray range. In XCT, the structural information in axial direction is not imaged directly but is reconstructed by the interferometric superposition of the light backscattered from the sample layers and a distinct reference wave. The spectral modulations of a layered sample are recorded with a high-resolution XUV spectrometer [3] leading to depth profiles of layered samples with nanometer precision. XCT measurements can be routinely performed using a laser-based XUV or soft x-ray source [4,5]. While depth information is obtained via a Fourier transform, material information is encoded in the spectral domain. In order to gain localized spectroscopic information with maximum resolution, the recorded spectra were processed as follows: The phase of the measured spectral reflectivity of the sample is algorithmically retrieved by a phase retrieval algorithm. With a filtering in the spatial domain, the spectral reflectivity of the sample from a well-defined depth can be obtained [6]. The phase information can thus be used for a quantitative reconstruction of the material composition of the sample.

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Presenting Author

Silvio Fuchs obtained a PhD in 2018 at the University of Jena, Germany. During his PhD work in the group of Prof. Gerhard Paulus, he developed a laser-based XCT setup, which is the basis for the investigation of layered nanostructured samples. He is the co-founder of Indigo Optical Systems GmbH, a spin-off of the University of Jena, which develops high resolution XUV spectrometers and performs XCT measurements of layered nanostructurs with relevance in EUV lithography.

P41

Combined Atomic Absorption /Optical Emission Spectroscopy for In-Situ Control of EUVL and X-Ray Optics Manufacturing

George Atanasoff, Christopher Metting

AccuStrata, Inc. 11900 Parklawn Drive, Rockville, MD 20852

The extremely thin metal-silicide and interface-engineered thin films, required for the deposition of EUVL and X-ray optics, fall below the detection threshold of the traditional *in-situ* methods utilizing direct monitoring of the substrate. Combined atomic absorption (AA) and broadband optical emission (OE) spectroscopy for monitoring the plasma area near the substrate is a solution, capable of providing real time information about the deposition rate and chemical composition of the individual films, process fluctuations and drifts.

Our latest development in *in situ* PVD process control for EUVL and X-Ray optics is presented. By monitoring both OE and element-specific AA, the technique provides more accurate values for atomic concentration and process conditions than AA or OE alone. Fiber-optics solution allows using 2 hollow-cathode sources for monitoring up to 4 individual elements simultaneously and supports 3 separate probe beams for physical modeling of the deposition rate, film composition and uniformity. The solution is a unique approach to controlling process stability and glitches. Machine learning is proposed for dynamic feedback control. Results from deposition of Mo, Si, B, W, Cu, Co, Al are presented. System accuracy is element dependent and is determined for each case. Technology validation for EUVL mirrors and X-Ray optics is reported.

Presenting Author

P42

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

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

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

Gigaphoton develops CO_2-Sn-LPP EUV light source which is the most promising solution as the 13.5nm high power light source for HVM EUVL. Unique and original technologies including; combination of pulsed CO_2 laser and Sn droplets, dual wavelength laser pulses for shooting and debris mitigation by magnetic field have been applied. We have developed first practical source for HVM; "GL200E" [1)] in 2014. Then it is demonstrated which high average power CO2 laser more than 20kW at output power in cooperation with Mitsubishi Electric[2)]. Pilot#1 is up running and it demonstrates HVM capability; EUV power recorded at 111W on average (117W in burst stabilized, 95% duty) with 5% conversion efficiency for 22 hour operation in October 2016[3)]. Availability is achievable at 89% (2 weeks average), also superior magnetic mitigation has demonstrated promising mirror degradation rate (= 0.5%/Gp) at 100W or higher power operation with dummy mirror test. We have demonstrated >300W operation data (short-term) and actual collector mirror reflectivity degradation rate is less than 0.15%/Gp by using real collector mirror around 125W (at I/F clean) in burst power > 10 Billion pulses operation[4)]. Also we will update latest challenges for >250W average long-term operation with collector mirror at the conference.

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Presenting Author

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

P43

Improvement of the Modeling of Atomic Processes in Plasmas for the Study of EUV Source based on a Data Driven Approach

Akira Sasaki

National Institutes for Quantum and Radiological Science and Technology
8-1 Umemidai, Kizugawa-shi, Kyoto, 619-0215 Japan

Atomic processes in Sn plasmas have been intensively investigated to achieve more the 250 W of the output power from laser pumped plasma (LPP) EUV source, that has enabled the high volume manufacturing (HVM) of semiconductor devices at the 5 nm process. The EUV emission arises from a large number of atomic transitions called unresolved transition array (UTA) from Sn^{5+} to Sn^{15+}. Although, the atomic processes in Sn plasmas have been investigated theoretically and experimentally, the characteristic feature of emission spectrum, which decides the conversion efficiency (CE) from the plasma, has not been fully understood. Improvement of the model is indispensable for further optimization of the source to produce higher output power for high-NA scanners. We try to determine accurate wavelength of UTAs taking the strong effect of configuration interaction (CI) into account based on a data driven approach, by investigating a wide variety of experimental and theoretical spectrum. We show a simple representation of the wavelength of 4d-4f, 4d-5p, and 4d-5f UTA as a function of the core charge and number of electrons in 4d shell. We suggest this representation may be applicable to heavier elements as well for modeling shorter wavelength sources at or less than 6 nm, for which the atomic structure is too complex to calculate using the present atomic codes and several UTAs are left unidentified.

Presenting Author

Akira Sasaki obtained Dr. Eng. from Tokyo Institute of Technology in 1981, and joined Japan Atomic Energy Research Institute in 1996, the organization of the institution has changed since to present National Institute for Quantum and Radiological Science and Technology. He is interested in the modeling of atomic process and spectroscopy of the plasmas based on the computational atomic data. He has carried out development and validation of large-scale collisional radiative models. He is also interested in the complexity of the materials and its modeling using statistical methods. He has been involved in the research project for the EUV lithography since 2003.

P44

Progress 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 (*Nature* 590, 576–579(2021)). Based on SSMB, high-average-power, high-repetition-rate and narrow-band EUV radiation can be generated. A compact SSMB EUV source is a promising candidate to serve the highvolume manufacturing of EUV lithography with a reasonable price. In this talk, we present the next-step SSMB experiment program and the progress of Tsinghua SSMB EUV light source development.functional groups for good solubility and adhesion to the substrate. Single component systems can also be designed following this approach by the incorporation of suitable PAGs and base quencher molecules in the main chain.

The polymers that will be presented have been evaluated so far as components of chemically amplified resist formulations exposed to EUV radiation (at 13.4 nm). The imaging chemistries have been investigated using spectroscopic techniques. A characteristic contrast curve shows that the resists are ultra-high sensitive (0.5 mJ/cm^2) using 5% PAG and 5% quencher with good contrast. In addition, they showed excellent etch resistance, similar to commercially available Novolac photoresists. Imaging experiments using EUV interference lithography have demonstrated capability for 22 nm hp with a dose of 10 mJ/cm^2 using 3 % PAG and 3% quencher with respect to the polymer and the PAG weight, respectively. We believe that this newly-developed material platform has a lot of room for improvement and further development will involve resolution and sensitivity optimization and absorption enhancement towards the targeted RLS specifications for high-NA lithography.

Presenting Author

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

P45

Towards Solid-state Laser-driven Plasma Sources of EUV light: An update on ARCNL's Source Research program (Invited)

Oscar Versolato

ARCNL

ARCNL's Source Department 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. I will give an overview of the research performed by the groups in our Source Department and present some recent highlights such as the contribution of multiply excited atomic states to the emission of EUV light from CO_2-laser driven plasma, new results of plasma, driven by 2-micron laser light, generated from pre-pulsed tin microdroplets, as well as new insights obtained on the fluid dynamics of droplet deformation upon laser-pulse impact.

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.

P46

Control of the Pressure-impulse Distribution in Laser-induced Tin droplet Deformation for Extreme-ultraviolet Nanolithography

Javier Hernandez-Rueda

Advanced Research Center for Nanolithography (ARCNL), Science Park 106, 1098 XG Amsterdam, The Netherlands

The precise control over the shape, size, and dynamic features of laser-generated tin targets highly conditions the efficiency and durability of extreme-ultraviolet sources for nanolithography. The laser-tin interaction generates a plasma, whose rapid expansion imprints a pressure impulse at the surface of liquid tin microdroplets. We experimentally and numerically investigate the influence of the droplet diameter and laser beam diameter on the pressure impulse that leads to deformation and propulsion of liquid tin microdroplets after laser impact. By using our stroboscopic imaging system, we record the evolution of the liquid tin morphology and determine the propulsion speed U and expansion rate $\dot{R}$. We find excellent agreement between the experimental U and $\dot{R}$ values and those obtained by radiation-hydrodynamic simulations. From the simulations, we extract the pressure impulse distribution at the droplet surface and the relationship between its width and the $\dot{R}/U$ ratio. We quantitatively show how the spatial distribution of the pressure impulse determines the balance between driving radial deformation and axial propulsion. Finally, we discuss how our findings on the pressure impulse can be combined with computational fluid dynamics simulations to gain further insight, and to link the initial plasma-driven dynamics (nanosecond-scale) to the subsequent fluid dynamics (microsecond-scale).

Presenting Author

Javier Hernandez-Rueda is currently a postdoctoral researcher within the EUV Plasma Processes group at the Advanced Research Center for Nanolithography in Amsterdam. He holds a PhD in physics awarded by the University Complutense of Madrid and has published over 30 research articles. His main research activity is to understand the dynamic processes over different time-scales that result of the interaction of fs and ns laser pulses with matter. In 2016, he was awarded a Marie S. Curie Individual Fellowship to investigate these dynamic processes in trapped nanoparticles at the Debye Institute in Utrecht. He has also worked on topics related to nonlinear optics at the Delft University of Technology and at the University of California Davis. His current research focuses on understanding the sequence of physical mechanisms that are triggered by the interaction of nanosecond laser pulses with liquid tin microdroplets.

P47

Optimizing the Performance of the EQ-10 Electroless Z-Pinch™ EUV Light Source (Invited)

Wolfram Neff

Energetiq Technology, Inc.
205 Lowell Street
Wilmington, MA 01887 USA

Energetiq manufactures the EQ-10 Electroless Z-Pinch™ EUV light source that has been a workhorse in EUV metrology since 2006. The performance of the light source is dependent on the operating parameters of the EQ-10.

This presentation is giving an overview of the dependence of the light source performance on its operating parameters that can help guide users to maximize the benefit of the EQ-10.

Presenting Author

Wolfram Neff's first experience with EUV came in 1996 when he worked on a z-pinch system as his graduate project in Germany. With EUV still in the far future at this point he worked mostly in development of plasma based coating technology, developing coatings for a wide range of applications, from resistors to pacemaker electrodes. Since 2019 he is back at his roots with Energetiq, where he is Principal Scientist and responsible for the EQ-10 Electroless Z-Pinch™ EUV Light Source product line. In addition to the Diploma in Physics from the University at Würzburg, Germany he holds a Master's in Physics from SUNY Buffalo, NY.

P48

Compact Storage Ring FEL: a kW-scale EUV Lithography Source

Rod Loewen

Lyncean Technologies, Inc.
47633 Westinghouse Drive
Fremont, CA 94539 USA

Present-day FELs have evolved from the successful development of accelerator and undulator technology at the core of fourth generation X-ray light sources pioneered at national laboratories. These sources rely on some form of electron accelerator linac to generate high peak currents, combined with low emittance and small energy spread beams, to achieve high single-pass FEL gain. High gain is a necessary condition at wavelengths where optics are inefficient, including EUV. The challenge with an FEL linac source for EUV lithography is how to adapt its high *peak power* capability to high *average power* capability. High average power requires high repetition rates, or high beam power, consequently demanding some form of energy recovery to be efficient. By requiring a linac FEL to run to saturation to improve the efficiency of extracted radiation power, the total length of the FEL device must be very long, on the scale of 100m or more. To make this approach economically and spatially efficient for chip production, a large scale FEL will need to feed many EUV scanners.

Is there a way to construct a more compact FEL? Yes, using an electron storage ring, or more accurately, a damping ring. A damping ring has a few advantages — a high average beam power and repetition rate (~100MHz), a low equilibrium emittance, and a high 'cooling' rate from synchrotron radiation. It also has disadvantages — the electron bunches have a modest peak current, there is limited room to insert an undulator system, and most importantly, the stored electron beam is 'heated' by the FEL process, increasing the equilibrium electron beam energy spread which directly limits the FEL extracted power. We present a design that overcomes the challenges of a storage ring EUV FEL by using a multi-pass EUV amplifier architecture in which high single-pass undulator gain can be maintained with a large energy spread beam using appropriate optics. The equilibrium energy spread during steady-state FEL operation is a balance between the FEL heating and synchrotron radiation cooling. The solution is consistent with the generation of kW-scale coherent EUV average power and is scalable. This approach also avoids FEL saturation while reducing the undulator system itself to ~20m in one straight of a racetrack storage ring that fits within a 10m x 40m footprint, a size more consistent with an EUV source installed in the sub-fab and matched to one or two scanners.

Presenting Author

Rod Loewen, CTO of Lyncean Technologies, Inc., is a technologist developing electron accelerators, laser systems, and feedback controls related to accelerator-based light sources spanning EUV to X-rays to Gamma rays. Rod has a Ph.D. in Physics from Stanford University and previously worked at the SLAC National Laboratory for a decade before co-founding Lyncean Technologies to develop inverse Compton storage ring sources, and more recently, coherent EUV source design for lithography.

P51

Progress and Outlook towards High-NA EUV Lithography (Invited)

Jara G. Santaclara, Rik Hoefnagels, Lidia van Lent-Protasova, Nadia Zuurbier, Herman Nicolai, Gijsbert Rispens, Arame Thiam, Joost Bekaert

ASML

Due to the high resolution required for future nodes and the sensitivity and stochastic challenges that current materials undergo, finding new photoresists is key. This is especially true for High-NA use cases, for which the resist ecosystem (i.e. High-NA EUV customers and resist suppliers) has identified the critical areas of development by means of a scorecard.

Therefore, state-of-the-art materials and processing needed for future applications are currently being evaluated. Stochastic defectivity performance is assessed by means of massive metrology for DRAM structures, finding for both CAR and MOR outstanding defect rate levels. Resolution is evaluated by high-NA exposures at Lawrence Berkeley National Laboratories and the Paul Scherrer Institute, where 8-9nm lines and spaces where achieved on Metal-Oxide Resist. Furthermore, by means of 0.33NA exposures at the ASML-imec Advanced Patterning Center, new patterning schemes (for both etch and tone inversion) for high resolution are being developed. This work gives a broad overview of the progress and innovations on high resolution photoresists and patterning processes, and highlights the key areas of development needed towards high-NA EUV lithography.

Presenting Author

Jara G. Santaclara obtained her PhD in Chemical Engineering from Delft University of Technology in 2017, focusing on light-matter interaction. She joined Resist and Processing group at ASML in 2017 to work on low-k1 enhancement techniques for 0.33 and 0.55 imaging (e.g. metal-containing resist, new mask absorber materials).

P52

High NA EUV Optics: a Big Step in Lithographic Resolution (Invited)

Lars Wischmeier, Paul Graeupner, Peter Kuerz

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

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

The latest scanner generation NXE:3400C uses 13.5 nm as operating wavelength. Since the last 2 years these scanners with 0.33NA are being used for high volume manufacturing and are now essential to produce leading edge semiconductor devices. To further increase the resolution of EUV scanners ZEISS is working on next generation EUV optics with an increased NA of 0.55. This next generation optics consists of a highly flexible illumination system and projection optics with NA 0.55 enabling single-exposure sub 8nm half-pitch resolution to allow scaling beyond the next decade.

In this presentation we will explain the system design of the high-NA optical column and we will report on the manufacturing status of mirrors and frames. Furthermore, the buildup of the infrastructure including mirror polishing, coating, surface figure metrology, mirror handling, and integration tooling will be shown.

Presenting Author

Lars Wischmeier received his PhD in semiconductor optics at University of Bremen, Institute of Solid State Physics in 2007 and started at Carl Zeiss SMT in Oberkochen the same year. Since 2015, he has been the Lead Systems Engineer in the ZEISS High-NA program.

P53

Progress in Metal Oxide Photoresists for High NA EUV Lithography (Invited)

Amrit K. Narasimhan

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

Inpria has pioneered the development of high-resolution metal oxide (MOx) photoresists designed to unlock the full potential of EUV lithography. These photopatternable hard mask materials enable extremely high-resolution lithography and wide process windows via their high EUV absorbance, low blur, and exceptional etch selectivity. These same capabilities place MOx photoresists as leading candidates for use in high Numerical Aperture (high NA) EUV lithography, where extremely tight pitches and the limited depth of focus of the high NA Optical system impose new challenges for photoresists.

In this contribution we will discuss recent advances in MOx materials and integration to address these challenges at relevant pitches, including High-NA imaging results on the Berkeley MET, etch properties of resist patterns through thickness, and advances in defect metrology and performance.

Improvement in photoresist performance must be accompanied by high-NA ecosystem development, which necessitates a multidisciplinary, industry-wide effort to advance the platforms enabling continued lithographic progress, including new developer infrastructure, track design, thin-film and defect metrology, MOx-specific underlayers, and etch processes. Advancements in each of these areas will, in turn, drive progress in the others.

Presenting Author

Amrit Narasimhan is a lithography engineer at Inpria, currently working on evaluating the performance of metal-oxide photoresists for EUV lithography, with a focus on novel materials and stochastic defectivity. He studied materials science and physics at Carnegie Mellon University, graduating with a BS in both in 2013, and a MS in materials science in 2014. He earned a Ph.D. in Nanoengineering at the College of Nanoscale Science and Engineering (SUNY Albany) in 2017, investigating the role of secondary electron interactions in EUV lithography in the Brainard and Denbeaux research groups.

P54

High NA EUV Research at Lawrence Berkeley National Laboratory (Invited)

Patrick Naulleau

Center for X-ray Optics, Berkeley Lab, Berkeley CA, 94720

Although high-NA EUV tool development is well underway, significant challenges remain. High NA not only stresses several current challenges, but more importantly it brings to light fundamentally new challenges. The most significant new challenge arises from angular bandwidth limitations of the mask multilayer requiring the use of anamorphic optics, or new multilayer material systems as well as polarization concerns that have never been an issue before for EUV owing to the relatively small angles involved. The most significant existing challenge being pushed to a fundamentally new regime with high NA revolves around stochastics in photoresist materials and exposure processes. As we approach the atomic scale, the quantized nature of light and materials is becoming a very significant effect in ultimate performance of the process. Addressing these challenges will require the understanding and control of materials and their interaction with EUV photons at the atomic scale. The Center for X-ray Optics at Lawrence Berkeley National Laboratory has developed a suite of tools and partnerships to address these issues. In this presentation, I will highlight some of these challenges and describe instrumentation developed to address them as well as recent research results.

Presenting Author

Dr. Patrick P. Naulleau has been involved in EUV lithography since 1997 when he joined Lawrence Berkeley National Laboratory (LBNL) to work in the area of actinic interferometric alignment. Since 2001 he has lead LBNL's EUV Patterning project starting with the 0.1-NA ETS optics and now the 0.3-NA MET optic. He is internationally recognized for leading EUV patterning studies and his contributions to EUV System designs. He is the lead author of chapter on EUV Patterning in the book EUV Lithography

P71

Introduction to imec (Invited)

Kurt Ronse

imec

Most people in this audience know imec for the advanced lithography activities. However, this time I will not focus on lithography but explain how imec has been founded and which other activities were present at the starting point of imec. Gradually the organization has grown and multiple international research programs have been started, covering logic, memory, photonics besides advanced lithography. The structure and way of working of the programs will be explained, as well as the other business models that have been deployed.

The next phase has been to combine the typical CMOS technology with sensors, MEMS and NEMS, leading to various applications, all intended to make life more enjoyable for all people, but to keep the planet also more sustainable. This section I will not go into, but the next speakers will all explain what applications they are working on, what their mission is and how they are all based on the fundaments of CMOS technology, where imec started.

Presenting Author

Kurt Ronse, Ph.D. has been working in the field of lithography at imec for almost 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 insertion of EUV lithography into HVM and on the extendibility of EUVL to the next technology nodes, and to which over 30 companies worldwide participate (chip manufactures, equipment and material suppliers, EDA/software companies).

Prior to joining imec, Ronse received a Ms. and Ph.D. degree in Electrical Engineering from the University of Leuven (Belgium).
Ronse has authored and co-authored numerous publications and is a frequent conference speaker, often times presenting invited and plenary papers, in the field of optical lithography (I-line, deep-UV, 157nm, 193nm, 193nm immersion) and EUVL. He is member of advisory groups of various lithography conferences and has been chairing several lithography conferences. He is member of the editorial board of the SPIE Journal of Micro/Nanolithography, MEMS and MOEMS (JM3).

In 2016, he has been elected Fellow of SPIE for achievements in microlithography and advanced patterning.

P72

imec Development and Manufacturing of Customized Device with imec's Technology (Invited)

Denis Marcon

imec

Microdevices are often the invisible innovation engines inside disruptive products. Microdevices, integrate advanced functionalities on tiny surfaces and are produced using advanced micromachining capabilities. But while their possibilities are huge, their development can be a challenge. Especially the part where a reliable manufacturing process needs to be developed in view of its future production.

The development of a manufacturable Microdevice requires access to the equipment you find in leading CMOS and MEMS foundries. However, typical MEMS and CMOS foundries are disinclined to take on these kind of projects because they are too busy with production runs. On the other side, university labs often won't provide the capabilities and expertise to realize a manufacturable process.

Imec's objective is to offer its advanced silicon pilot line, technical expertise and IP to allow the development of advanced MEMS and microdevices. And guide them all the way to prototyping and manufacturing.

In this talk, imec will review imec's capabilities and expertise to develop microdevices as well as imec's established procedure to bring a component from early stage prototype into a qualified product.

Presenting Author

Denis received an M.S. degree from the University of Padova in 2006. Subsequently, he received the degree of Doctor in Engineering (Ph. D.) from the Catholic University of Leuven and imec in 2011. He is the leading author or co-author of more than 50 journal papers or conference contributions. Currently, he is a senior business development manager at imec. He is directly responsible for the partnerships with imec in dedicated development and manufacturing of Si-based devices, MEMS and microsystems, sensors and actuators, and GaN power electronics.

P73

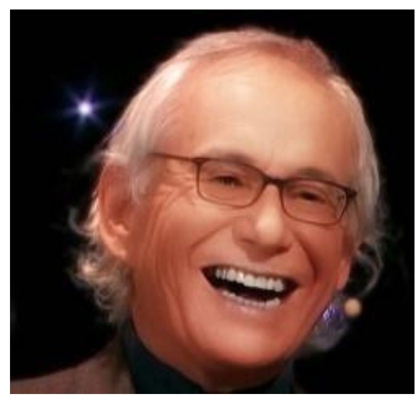
Tour of the Attolab (Invited)

John Petersen

imec

Imec's AttoLab is the first industrial laboratory capable of watching the ultrafast dynamics of photoresists following 13.5 nm, EUV exposure, and for emulating high-numerical – aperture (NA) exposure on 300-mm wafers using two-beam EUV interference. The two respective beamlines are powered by a laser based high-harmonic generation EUV source. Its capabilities have recently been proven by imaging 20 nm pitch lines and spaces using Lloyd's Mirror interference lithography. In parallel, time-averaged and time-resolved techniques for studying the ultrafast dynamics of photoresists induced upon EUV exposure, coherent diffractive imaging to study resist interfaces, and more sophisticated interference lithography techniques for printing sub-22 nm pitches on full 300 mm wafers are being developed. Taking advantage of the bright and short EUV pulses now available at imec we will be able to contribute to a smooth transition towards next generation high-NA lithography.

Presenting Author



John Petersen is a principal scientist in the advanced patterning group at imec and with Paul van der Heide, is the co-originator and coleader of imec's AttoLab, the first industrial ultrafast dynamics laboratory of its type that is chartered for the development of spatiotemporal metrologies needed for the production for sub-3 nanometer nanoelectronics and nanophotonic devices. Concurrently, Petersen is an adjunct professor of physical chemistry at the University of Maryland, a SPIE Fellow and a former Fellow at SEMATECH. Since 1980, he has been at the forefront of the development of lithography for the fabrication of semiconductor devices, where he continues to research the interplay between the physics and the chemistry of the photoresist imaging process. John has given more than nineteen invited talks, taught many professional classes for SPIE and imec. He has published eighty-seven papers, forty-five of them as lead author/researcher, holds twelve patents and co-won the SEMI 2006 Innovation Award for the Maxwell solver EMF3. He has worked at Texas Instruments, Shipley Company, Shipley Microelectronics, SEMATECH, Petersen Advanced Lithography, Periodic Structures and now imec, Leuven, Belgium.

P74

One Planet: Nanoelectronics and digital technology for food and health (Invited)

Chris Van Hoof

imec

We are faced with global challenges related to health, food, sustainability and the environment. While these are formidable challenges, they also represent a gigantic opportunity to improve people's lives on a global scale while at the same time creating new economic opportunities. The OnePlanet Research Center is a multi-disciplinary collaboration between imec, Radboud University & Medical Center, and Wageningen University & Research where nanoelectronics and analytics innovations are used to solve problems related to personalized health, personalized nutrition, sustainable food production and reduced environmental impact. In his presentation Chris will show innovations we are creating and validating such as sensors for monitoring our nutrition and metabolic health, environmental sensors monitoring nitrogen emission, crop sensors for indoor farming, and our work towards digital twins.

Presenting Author

Chris Van Hoof is Vice President R&D at imec and General Manager of the OnePlanet Research Center in Gelderland. Chris believes preventive health, personalised nutrition, sustainable food production and reduced waste are essential enablers of improving our world for the generations to come. And he is convinced that technology (hardware and AI) are key tools to make that happen. After receiving a PhD in Electrical Engineering from the University of Leuven in 1992, Chris has held positions as manager and director at imec in highly diverse fields spanning technology, circuits, systems, data and applications. Apart from delivering industry-relevant innovative solutions to customers, his work also resulted in five startups (four in the healthcare domain). He is also full professor at the University of Leuven and an imec Fellow. Although OnePlanet Research Center started just over 2 years ago, it has already built up a team of 70 scientists and engineers, who create innovations in close collaboration with teams from the founding organizations imec, Radboud University and Medical Center and Wageningen University and Research.

P75

Distruptive Pixel Technologies Enabling Affordable, High Quality Infrared Imaging (Invited)

Pawel Malinowski

imec

Image sensor technology serves a multitude of consumer devices, with already several cameras found in an average smartphone. At the same time, imagers used in new machine vision applications - for sensing rather than taking photographs – need new approaches and architectures. One of the important directions is extending the range of Si-based sensors into the near infrared (NIR) and short-wave infrared (SWIR).

Imec has been exploring integration of novel absorber materials (such as organic and quantum dots) to enable monolithic imagers with cut-off wavelengths beyond Si absorption edge. The activities comprising material screening, stack development, pixel engine design, process integration, camera buildup and characterization led to development of state-of-the-art SWIR image sensors with sub-2 µm pixel pitch and high quantum efficiency. This technology enables both image quality improvement (by increased resolution) and throughput scaling (by reducing the footprint and wafer-level fabrication). In this presentation, we will show the processing approach, performance benchmarking and examples of applications enabled by this affordable SWIR technology.

Presenting Author

Pawel E. Malinowski received the M.Sc.Eng. degree in electronics and telecommunications from the Lodz University of Technology, Poland, in 2006. In 2011, he received the Ph.D. degree in electrical engineering from the KU Leuven, Belgium. Pawel is working at imec since 2005, always with different types of novel photodetectors. He is Program Manager "Pixel Innovations" and he focuses on disruptive optical sensor technologies, including new types of image sensors enabled by thin-film semiconductor integration.

Pawel has coauthored more than 40 publications and submitted 5 patent applications. He served on the ODI Committee (Optoelectronics, Displays, and Imagers) of the 64th and 65th IEDM conference.

P76

Nanotechnology and the Energy Transition (Invited)

Jozef Poortmans

imec

Nanotechnology and nanomaterials are enablers of innovative devices and systems in the domain of ICT, wireless communication, medical devices, ... However it is largely ignored that also in the domain of Energy these developments will have major impacts. It is clear that in the domain of Smart Grids and Smart Cities, sensors and the wireless communication amongst these sensors will play a crucial role, but the focus of the presentation will be on how electricity generation, electrical energy storage and power electronics will be influenced by the developments in the nano-domain. The presentation will provide examples how nanomaterials and –technologies are incorporated in advanced and novel photovoltaic devices in order to increase their performance and achieve a further cost reduction. Intermittent sources like wind and solar have to be deployed hand-in-hand with new and cost-effective energy storage solutions as to ensure continuous equilibrium between electricity generation and consumption. Electrochemical storage in batteries near the location where the energy is generated and consumed is certainly part of the solution for the day-to-day storage. In this domain the developments on nanomaterials will improve the energy and power density of batteries by enabling nanosized particles with mixed ionic and electronic conductivity for the electrodes whereas the amount of passive material is reduced by the use of thin solid-state electrolyte layers. Similarly, nanotechnical features can be used to improve electrolysers converting electrical energy into chemical energy by electroreduction of H_2O to generate H_2 or CO_2-electroreduction to enable CO_2-circularity. Storage under the form of molecules would be a very elegant way to solve the seasonal storage question.

Presenting Author

Jozef Poortmans received his degree in electronic engineering from the Katholieke Universiteit of Leuven, Belgium, in 1985. Presently, he is Program Director of the Energy activities of imec. In 2013 he was also appointed imec Fellow. Since 2008 he is part-time Professor at the K.U.Leuven, where he teaches courses on photovoltaics and materials in electrical engineering. In 2013 he became also part-time Professor at University Hasselt where he teaches a course on analog electronics. Since September 2016 he is Coordinator R&D-strategy of EnergyVille, an institutional partnership between imec, VITO, KULeuven and University Hasselt aiming at the development of technologies and demonstrations for the Energy Transition.