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Workshop Abstracts

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Contents

Abstracts

(Listed by Paper number)

P1

Canonical Phase Measurement in Quantum Mechanics (Keynote Presentation)

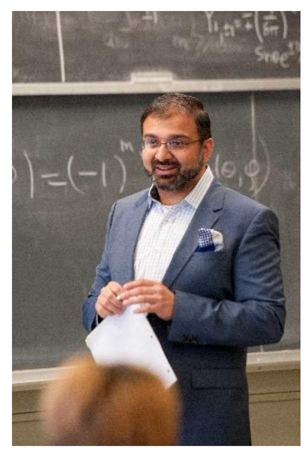
Irfan Siddiqi

University of California Berkeley and Lawrence Berkeley National Lab

Modern metrology and communication technology relies on encoding information in electromagnetic waves, typically as an amplitude or phase. While current hardware can perform near-ideal measurements of photon number or field amplitude, to date no device exists that can even in principle perform an ideal phase measurement. I will discuss the implementation of a single-shot canonical phase measurement on a one-photon wave packet, which surpasses the current standard of heterodyne detection and is optimal for single-shot phase estimation. Our system adaptively changes its measurement basis during photon arrival and allows us to validate the detector’s performance by tracking the quantum state of the photon source. These results demonstrate that quantum feedback can both enhance the precision of a detector and enable it to measure new classes of physical observables.

Presenting Author

Irfan Siddiqi is a Faculty Scientist at Lawrence Berkeley National Laboratory, a Department of Energy Office of Science lab, and a Professor of Physics at the University of California, Berkeley. Irfan completed his undergraduate degree in chemistry & physics and PhD in applied physics from Harvard University and Yale University, respectively. Irfan joined the physics department at UC Berkeley in the summer of 2006. Siddiqi and his research group, the *Quantum Nanoelectronics Laboratory*, focus on the development of advanced superconducting circuits for quantum information processing, including computation and metrology. Additionally, Siddiqi runs the *Advanced Quantum Testbed* at Lawrence Berkeley National Laboratory. Siddiqi is also the founder of the interdisciplinary *Center for Quantum Coherent Science* at Berkeley. Irfan is known for seminal contributions to quantum measurement science, including real time observations of wavefunction collapse, tests of the Heisenberg uncertainty principle, quantum feedback, and the development of a range of microwave frequency, quantum noise limited analog amplifiers. Irfan is a fellow of the American Physical Society, and in 2006 was awarded the George E. Valley Jr. prize for the development of the Josephson bifurcation amplifier. Siddiqi is a recipient of Young Investigator Awards given by the Navy, Airforce, and DARPA, the Hellman Family Faculty Fund, and the UC Berkeley Chancellor’s Partnership Faculty Fund. Siddiqi is among five faculty members who received the "2016 Distinguished Teaching Award," UC Berkeley’s most prestigious honor for teaching.



P2

EUV lithography Today and Extension for the Next Generation (Keynote Presentation)

Britt Turkot

Intel Corporation

Extreme Ultra-Violet lithography offers a compelling alternative to 193nm-immersion lithography, improving imaging resolution and reducing a key contribution to Edge Placement Error (EPE). Progress continues in the development of EUV exposure tools, with source power meeting the roadmap target for EUV insertion as well as demonstrating improvements in system availability and infrastructure such as pellicle membrane manufacturing and EUV photoresist materials. Extension of EUV for the next generation of 0.33NA as well as high NA will require continued improvements of the EUV ecosystem. This presentation reviews the current status and challenges of EUV lithography for High Volume Manufacturing (HVM) as well as expectations for next generation EUVL.

Presenting Author

Britt Turkot is a senior principal engineer and engineering group leader with Intel's Portland Technology Development Lithography organization where she is the EUV program manager for Intel. She has been with Intel since 1996 after receiving B.S., M.S. and Ph.D. degrees in Materials Science and Engineering from the University of Illinois at Urbana-Champaign.

P3

Enabling the Semiconductor Roadmap from a Multi-Angled Approach (Keynote Presentation)

Steven Welch

Applied Materials

With the ever-increasing demand and pervasiveness of semiconductor technologies, the industry is continuously looking for novel ways to both extend the most advanced technology nodes further as well as provide new enhancements to established nodes. Innovations in lithography, new materials, integration schemes and architectures are all being explored to extend device performance scaling. The advancements of new memory technologies endeavor to enable scaling in logic devices, fill gaps in stand-alone memory performance for ever-expanding data demands, as well as facilitate the quickly growing AI applications space. Opportunities to extract performance at lowest power and smallest form factors exist - from the transistor to the interconnects to the package and beyond. However, all must be done with complexity, cost, yield and speed in mind. In this talk, I will discuss how AMAT is assessing and approaching these needle-moving opportunities.

Presenting Author

Steven Welch is currently Senior Director of Strategy for Applied Materials' Advanced Product and Technology Development group. In this role, he is responsible for identifying and synthesizing key inflections in the longer-term Semiconductor technology roadmap, as well as enabling disruptive technology development and business growth strategies to intercept these emerging opportunities. With over 20 years in the industry, Steven started his career in 1998 as a photolithography engineer at IBM's Storage Systems Division in San Jose, California. Since then, he has held marketing and strategy leadership positions in KLA-Tencor's wafer inspection, Applied Materials' etch, and ASML's holistic lithography businesses. Steven holds a B.S. in Chemistry from Harvey Mudd College and MA & MBA degrees from the University of Pennsylvania's Wharton School of Business.

P4

EUV Lithography Research and Development Activities in Japan (Keynote Presentation)

Takeo Watanabe

University of Hyogo

As described on the IRDS roadmap, logic foundry producers have announced their commitment to producing products using extreme ultraviolet (EUV) with a target date of early 2019 and possible late in 2018 from 7 nm node. The technology issues are 1) EUV resist which satisfy high resolution, high sensitivity, low LER, and low outgassing, simultaneously, 2) high power and stable EUV light source, 3) pellicle with high transparency and long lifetime, and 4) defect free EUV mask fabrication.

From 1995, EUV R&D was started at University of Hyogo. Up to now, many significant technology research and development of EUV lithography were done by this research group. Using NewSUBARU synchrotron light source at University of Hyogo, resist fundamental work for the achievement of high sensitivity and low LER has been carried out. The Mask defect inspection system on a basis of EUV microscope and coherent scatterometry microscope was developed. And using high power EUV generated by 10.8 m long undulator, EUV Irradiation regime and outgassing of pellicle and mask materials have been evaluated.

EIDEC is the EUVL consortium in Japan, which was started at 2013. The recent work of EIDEC of EUV resist and mask will be presented. In addition, for the future patterning method with continuing Moore’s law, the possibility of EUV lithography in shortening the wavelength to 6.75 nm will be discussed.

Presenting Author

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

P11

Selective and Directional Patterning of Ni for EUV Masks Application (Invited)

Jane P. Chang

Department of Chemical and Biomolecular Engineering,
University of California, Los Angeles (UCLA), Los Angeles, CA 90095

The talk will discuss pertinent surface chemistries required to achieve a highly anisotropic etch of Ni for EUV masks, with the goal of realizing a nearly vertical sidewall angle of 90º. The selection of gas phase chemistries is crucial to the success of the patterning process, therefore the selection criteria, based on thermodynamic and kinetic assessment, will be explained. The general approach combines reactive ion etching with atomic layer etching processes where the sequential surface reactions starts with controlled surface modification, followed by selective removal of the modified layer. This general approach can be applied to a variety of EUV mask materials, making it possible to tackle more complex material systems as needed.

Presenting Author

Dr. Jane P. Chang is a Professor and the William F. Seyer Chair in Materials Electrochemistry in the Department of Chemical and Biomolecular Engineering at UCLA. Her research focuses on the synthesis and chemical processing of novel and multifunctional materials, atomistic understanding of solid-state interfaces, and their applications in microelectronics, optoelectronics, microsensors, and energy storage devices. She is the author of 120 journal publications, including a book and a book chapter, holds 4 U.S. patents, and has given more than 190 invited presentations at many international conferences, academic institutions, and industry throughout the world. She received the Faculty Career Development Award from the National Science Foundation in 2000, a Chancellor's Career Development Award from UCLA in 2000, the Young Investigator Award from the Office of Naval Research in 2003, and the AVS Peter Mark Award in 2005. She also received the TRW Excellence in Teaching Award in 2002 and the Professor of the Year Award from the Chemical and Biomolecular Engineering Department at UCLA in 2003, 2004, and 2009. She is a Fellow of AVS and received the AVS PSTD Plasma Prize in 2018.

P12

Fabrication and Evaluation of SiN-based EUV Pellicle (Invited)

Ha Neul Kim[1], Yong Ju Jang[2], Seong Ju Wi[1], Juhee Hong[3], Chang Hoon Lee[3], Kee Soo Nam[3] and Jinho Ahn[1,2]

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The specification of EUV pellicle is a moving target. Mechanical robustness and EUV transmittance were the major concerns in the beginning of EUV pellicle development. And then the thermal emissivity during EUV exposure became a big issue. Extremely low EUV reflectivity is another strict property required for EUV pellicles. Even though all these requirements have not been met yet, continuous improvements are achieved. Silicon nitride has been suggested as one of the candidates for core layer of EUV pellicle due to its mechanical strength and thermal stability at high temperature. In this paper, properties of SiN-based EUV pellicle related to the optical, mechanical and thermal specifications will be presented. And also the influence of imaging property and lifetime of the pellicle on the material and size of the particles on pellicle surface will be discussed.

Full-size pellicle with SiN core layer was fabricated by low pressure chemical deposition of SiN film and Si back-etching with KOH solution. Imaging property of the pellicle was evaluated by home-made EUV scanning lensless imaging (ESLI) tool using pelliclized patterned EUV mask. Mechanical and thermal properties of pellicle were investigated by measuring a deflection of the pellicle depending on pressure differential through a bulge test and UV-laser induced heat load test, respectively.

Presenting Author

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

P13

Exploration of Different Simulation-based Methods to Reduce Stochastic Failure Risk (Invited)

Kevin Lucas

Synopsys, Austin, TX

Abstract to be published.

Presenting Author

Kevin Lucas received his Ph.D. in Electrical and Computer Engineering at Carnegie Mellon University in 1995 and joined Motorola Semiconductor. At Motorola he worked on OPC, DUV & EUV lithography simulation and lithography design rules. In 2000, he was an OPC assignee at IMEC and in 2003-2006 he was an OPC assignee at the Crolles2 Alliance. In 2006 he joined Synopsys in Austin, TX where he currently is Director of Product Engineering for compact and rigorous modeling applications. He has published > 150 technical papers and holds a few US patents.

P14

Ion Beam Technology Roadmap for EUV Mask Deposition and Absorber Etch Processes (Invited)

Sandeep Kohli, Meng Lee, Boris Druz, Adrian Devasahayam

Veeco Instruments, 1 Terminal Drive, Plainview, NY 11803

As the adoption of extreme ultra-violet (EUV) lithography accelerates in 7nm and lower process modes, ion beam technology is finding large applications in meeting existing and future challenges [1,2]. For example, significant improvements in the Ion Beam Deposition methods for Mo/Si mask blank are currently progressing to further improve reflectivity, defects, and yield of mask blanks. These methods involve significant improvements in hardware, process methods and materials engineering.

Another area where Ion Beam technology is currently being explored is etch application for alternate absorber layers. While Tantalum Nitride (TaN) absorber layer currently meets the requirement of existing EUV technology, need for thinner absorber layer with high extinction coefficient for future application is becoming more obvious. Amongst the materials for alternate absorber being currently explored, Nickel (Ni), Cobalt (Co) and Palladium (Pd) based alloys lead.

We provide here an overview of improvements in ion beam deposition methods for mask blank manufacturing using Veeco NEXUS IBD-LDD Ion Beam Deposition System. A Summary of recent work for application of Veeco IBE systems to the patterning of EUV high-k mask absorber structures will also be presented [3].

References:

[1] Antohe et al.; Proceedings of the SPIE, Volume 9048, id. 90480H 8 pp. (2014).
[2] Devasahayam et al; Proceedings of International Workshop on EUV Lithography, June 12-15, 2017, CXRO, LBNL , Berkeley, CA (2017)
[3] Rook et al.; Proc. SPIE 10809, International Conference on Extreme Ultraviolet Lithography 2018, 108090F (3 October 2018);

Presenting Author

P15

Stochastic Investigation of the Impact of Absorber Variations on Wafer Patterns (Invited)

Derren Dunn[a)], Lawrence S. Melvin III[b)], Tim Fühner[b)]

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b) Synopsys, Inc. 2025 NW Cornelius Pass Road, Hillsboro, OR 97124, USA

Pattern fidelity in EUVL is extremely sensitive to variations of both the multi-layer mirror and the absorber. Pronounced mask 3-D effects, shadowing and the non-telecentricity of the EUV projection system exacerbate the prediction of patterns and thus their control. Moreover, the relatively low signal-to-noise ratio and the high energy of EUV photons cause an additional stochastic variance of patterns that must be considered. These effects include line-edge-roughness (LER) and line-width-roughness (LWR) but also other stochastic failures including occasional unexposed “roadblocks” in the resist that prevent it from being developed entirely down to the bottom. In this study, we have examined the stochastic impact of absorber variations on wafer patterns. Specifically, we have studied the influence of absorber pattern variation in OPC corrections using stochastic exposure and photo-chemical models. Because of the delay in the introduction of EUV, relatively aggressive optical proximity correction (OPC) and inverse lithography (ILT) approaches will be required early on. The so-obtained corrected mask layouts typically contain high-frequency structures that cannot be reproduced during the mask making process, which materializes as corner rounding and an erosion of small features. Although these degradations may be tolerable under nominal conditions, the EUV-specific stochastics, including shot noise and chemical inhomogeneities, drastically increase the susceptibility to defects. We have approximated the mask writing imprecisions by smoothing the corrected mask layout using Gaussian filter compositions. We have then conducted rigorous, stochastic simulations and compared the impact of different levels of smoothing. Out of the multitude of so-obtained results, we have revisited those that show a stochastic failure and conducted an in-depth analysis of the contributing factors that led to the defect.

Presenting Author

Derren Dunn is currently Computational Patterning Team Manager at IBM’s Albany Nanotechnology Laboratory where he leads a team of engineers responsible for advanced resolution enhancement technology, design technology co-optimization, and the interaction of computational patterning solutions with advanced node mask technologies.

Prior to serving as Advanced Patterning Technology Lead, Derren held several team lead and management positions in computational patterning within IBM's Semiconductor Research and Development Center in Hopewell Junction New York. He has deep experience in developing optical, resist, and process bias models for use in optical proximity correction and advanced lithography simulation.

Derren holds a Ph.D. degree in Materials Science and Engineering from Northwestern University. After completing graduate work at Northwestern, Derren completed a post-doctoral fellowship in the Surface Chemistry division of the Naval Research Laboratory in Washington, D.C., where he studied surface chemical aspects of friction and wear. Dr. Dunn continued his post-doctoral studies at the University of Virginia where he worked on a virtual integrated prototyping project to explore new methods of simulating key semiconductor manufacturing processes. As part of this work, he developed new techniques for focused ion beam tomographic reconstructions that leverage secondary ion mass spectroscopy chemical maps in conjunction with secondary electron imaging to construct three-dimensional structural and chemical maps used to quantitatively explore nanoscale integrated circuit structure-property relationships. He has authored or co-authored more than 40 refereed articles and holds several patents in the United States and internationally.

P16

Next Generation EUV Mask Blank Absorber Development (Invited)

Vibhu Jindal, Shuwei Liu, Kan Fu, Weimin Li, Wen Xiao, Khor Wui, Madhavi Chandrachood

Applied Materials

As EUV Lithography progresses in high volume production, the next generation challenges for EUV Mask have started to emerge. The development of thinner absorber with high-k (extinction coefficient) material is one of the critical needs to address mask 3D (M3D) effects. While multiple material systems can demonstrate higher extinction coefficient, there are several other properties which are required for demonstration and selection of good EUV mask absorber material. The material system should be single phase and amorphous, smooth surface and stress controlled, etchable in traditional chemistries with high fidelity, etch selective and good adhesion to Ru cap layer, cleaning chemistry compatible, hydrogen resistant, inspectable in deep UV, along other physical and chemical properties. This requires holistic and systematic approach for material development and selection with mask processing validation at every step. In this work, Applied Materials will provide the framework which enables the development and selection of EUV advanced absorber meeting such stringent material properties and specifications. Evaluation from multiple advanced absorber material candidates will be presented which have gone through the framework successfully. Finally, patterning results of sub 40nm advanced absorber mask will be demonstrated achieving less than 2% reflectivity.

Presenting Author

P17

Development of EUV-ptychography Microscope: EUV Scanning Lensless Imaging (ESLI)

Dong Gon Woo[1], Young Woong Kim[1], Yong Ju Jang[2], Seong Ju Wi[1], Seung Hyuk Shin[3], Whoi-Yul Kim[3] and Jinho Ahn[1,2]

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[2] Division of Nanoscale Semiconductor Engineering
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As the device scaling continues, metrology and inspection techniques are required to improve their resolution further. In our laboratory, EUV scanning lensless imaging system (ESLI) which uses coherent EUV light source generated by high harmonic generation (HHG) and ptychographical iterative engine (PIE) has been developed.

However, the spatial resolution of this system is limited by several noises such as probe and stage drift, intensity fluctuation of the light source and the other background noise. The resolution was improved by the modified algorithm to minimize the influence of such noises and the Fourier magnitude constraint applied to the initial probe information and position correcting calculation of initial probe position. In order to evaluate the improved performance of ESLI, line and space patterns of EUV mask was observed, and the results were compared with those obtained by CD-SEM. ESLI shows detectability of micro-bridge type defect which is compatible with the CD-SEM result. Also, ESLI was tested to confirm the applicability to investigate the size of killing defect on the pellicle.

Presenting Author

Dong Gon Woo is a graduate student under prof. Jinho Ahn in Hanyang University, South Korea.

P18

Study of the Reflection-field Features of EUV Mask Blank with Defects in Multilayers

Guannan Li[1,2], Lituo Liu[1],Weihu Zhou[1],Xiaobin Wu[1],Xiaomei Chen[1], Yu Wang[1], Dongbin Mei[1]

[1]Institute of Micro-electronics of the Chinese Academy of Sciences, Beijing 100029, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China

Manufacture of defect-free extreme ultraviolet (EUV) mask is one of the most critical challenges for EUV lithography. In this paper, we study the features of reflective field of EUV mask blank by simulation in detail. Based on the size of EUV mask multilayer structure, which is smaller than wavelength of EUV source, we use the finite-difference time-domain (FDTD) method to analyze the disturbances of reflection field caused by buried defects in multilayer. Different kinds of buried defects' properties include sizes and positions are taken into account to investigate their different impacts on reflection field of mask blank. Also, we study both the near field distribution and far field distribution of the reflection field in the situation of no defect and various defects respectively. The results show that the features of reflection field are obviously different with the change of positions and sizes.

Presenting Author

Guannan Li received her Bachelor's in School of Electrical Engineering & Automation from Harbin Institute of Technology in 2017. She is currently pursuing a master's degree in Optical Engineering at University of Chinese Academy of Sciences, Beijing, China. Her main research focuses on simulation study of EUV mask defect inspection.

P19

Thermo-mechanical Characteristics of EUV Pellicle with Particle Contamination

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

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[2]Division of Nanoscale Semiconductor Engineering
Hanyang University, 222, Wangsimni-ro, Seongdong-gu, Seoul, Republic of Korea

Even though the requirements on EUV transmittance and reflectance have not been met yet, continuous improvements are achieved. And now we need to check the influence of particle adders on pellicle characteristics. In this study, the pellicles contaminated by particles with various components and sizes has been investigated.

SiN_x/Ru double-stack pellicles were fabricated by low pressure chemical vapor deposition and sputtering. Particles of Ti, C, Cr, Fe which are the main contamination species in EUV scanner were dispersed in IPA and transferred to the pellicle surface through spin coating. The distribution of particles was observed by optical microscopy. Thermo-mechanical characteristics of pellicle were evaluated by heat load test equipment with 1:9 on/off ratio using 355nm UV laser.

The size of the particles transferred by spin coating method was observed to be in the range of C; 5~8um, Fe; 13~16um, and Ti; 15~21um. The temperature of pellicle surface during UV exposure increases due to the localized heating of the micro-scale particles. The lifetime measured at 400W EUV equivalent power shows significant instability due to particle contamination under on/off cyclic exposure condition. The pellicles with carbon and metal particles are fractured with the measured temperature of ~1050°C and 750~800°C, respectively.

Presenting Author

Ha Neul Kim is a graduate student of Prof. Jinho Ahn in Hanyang University.

P20

Study of Feature Extraction and Classification of Defects from EUV Mask with Arbitrary Pattern Using Convolutional Neural Network

Lituo Liu[1], Guannan Li[1,2], Weihu Zhou[1], Xiaobin Wu[1], Dongbin Mei[1], Yu Wang[1]

[1]*Institute of Micro-electronics, Chinese Academy of Science, Beijing, 100029, China*
[2]*University of Chinese Academy of Sciences, Beijing, 100049, China*

In order to extract the EUV mask defect features from the images recorded by the EUV CCD, and classify different kinds of defects, the method of Convolutional Neural Network(CNN) was introduced. The mechanism of defects disturbance to the diffraction field reflected by the arbitrary patterned EUV mask was analyzed and subsequently a disturbance model was established. The model provides a explanation and theoretical basis for feasibility of using the CNN to extract and classify defects from EUV mask.

Presenting Author

Lituo Liu is the research assistant at the Institute of Micro-electronics, Chinese Academy of Sciences. He received his Ph.D. degree from Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences in 2012. Since graduation, he has engaged in research on optical method for defect inspection technology in semiconductors.

P22

Maskless, High-NA EUV Scanner

Kenneth C. Johnson

KJ Innovation, 2502 Robertson Rd., Santa Clara, CA 95051

The resolution capability of EUV lithography has reached parity with e-beam, raising the possibility that maskless EUV could displace e-beam for low-volume wafer production and mask writing. This paper outlines a maskless, 0.55-NA EUV scanner design, which would have a write time of under 3 hours per 200-mm wafer, or 2 hours per 150-mm mask, at an exposure dose of 200 mJ/cm^2 with an 8-nm writing grid step. The scanner partitions 13.5-nm illumination from a commercial EUV LPP source into approximately 2 million focus points, which are individually modulated via MEMS microshutters at a 24 kHz frame rate. The focal point array is imaged onto the writing surface, which is scanned in synchronization with the modulators to construct a digitally-synthesized, raster exposure image.

Presenting Author

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

P23

Defectivity Improvements Enabling HVM for EUV Scanners

Mark van de Kerkhof, Christian Cloin, Andrei Yakunin, Ferdi van de Wetering, Andrey Nikipelov, Fabio Sbrizzai

ASML Netherlands B.V., De Run 6501, 5504 DR Veldhoven, The Netherlands

With the introduction of the NXE:3400B scanner, ASML has brought EUV to High-Volume Manufacturing (HVM). In this context, ASML is pursuing a dual-path approach towards zero reticle defectivity: EUV-compatible pellicle or zero particles towards reticle by advanced particle contamination control.
This paper will focus on the latter approach of advanced particle contamination control and will show that we are able to reduce particle contamination towards reticle to a level that is compatible with HVM requirements for sub-10nm node lithography.

This paper will present several advancements in understanding and control of flow-related forces on particles as well as particle forces related to EUV-induced plasma, for EUV sources up to 250W and beyond.

It will be shown that with these particle contamination control concepts, ASML can offer customers the freedom of choice between pellicle or pellicle-less operation for HVM-EUV, depending on chip design, other details of the layer to be exposed and fab operational requirements.

Presenting Author

Mark van de Kerkhof began his career in 1995 at ODME, developing a novel DVD mastering process, and later worked on early deep-UV and immersion recording technologies for Blu-Ray. In 1999 he joined ASML as senior designer, working on miscellaneous sensors and imaging optics in both DUV and EUV systems, and was responsible for the overall technical definition and integration of the NXE:3400B EUV scanner as Product System Engineer. He is currently responsible for EUV Defectivity and Scanner Plasma Technology. He has published more than 25 papers and is (co-) inventor of more than 70 USA patents.

P24

Optics for EUV Lithography (Invited)

Sascha Migura

Carl Zeiss SMT GmbH, Germany

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

Due to its very short operating wavelength, EUVL holds the potential for a large gain in resolution. One challenge is the development and application of an advanced optics technology: All optical elements are high precision multilayer-coated mirrors – eventually integrated into full optical systems. Over the years, the focus of the optics has moved from R&D to commercial production. Nowadays, optics for EUVL are being produced in significant numbers as commercial sub-systems for EUVL scanners.

The next step of EUVL is already in the making: For now, high-NA EUV is envisioned to be the summit of lithography with ultimate resolution – supporting the continuation of the shrink roadmap.

The status of the commercial optics for EUVL and the current state of the high-NA EUV optics development will be outlined.

Presenting Author

Sascha Migura has been employed by Carl Zeiss SMT GmbH since finishing his PhD in physics in 2006 at the University of Bonn. He mainly worked on EUV lithography optics and was responsible for the optical designs of the Starlith® 3100 and Starlith® 3300. Sascha Migura was also Lead System Engineer of the pre-development of the High-NA EUV lithography optics.

P25

Overview, Status and Performance of the 0.5-NA EUV Microfield Exposure Tool at Berkeley Lab

Chris Anderson

Berkeley Lab, 1 Cyclotron Road Mail Stop 2R0400, Berkeley, CA 94720 USA

To meet industry demand for EUV materials testing capabilities down to the 2 nm lithography node, the EUV Materials Testing Center at Berkeley Lab has been expanded to include a 8-nm resolution, 0.5-NA EUV microfield exposure system with robotic sample processing and exchange tailed for research. This paper provides an overview of the current status, performance, and capabilities of the new exposure system and ancillary ecosystem.

Presenting Author

Chris designs, builds, and operates EUV and x-ray optical systems used for science and research and Berkeley Lab.

P31

Assessing the Impact of Latent Imaging of Resists *via* Grazing Incidence Resonant X-ray Scattering

Isvar. A. Cordova[1,2], Guillaume. Freychet [1,4], Scott. D. Dhuey[3], Alex Hexemer [1], Cheng Wang[1], Patrick Naulleau[3]

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[2]Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA
[3]Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA
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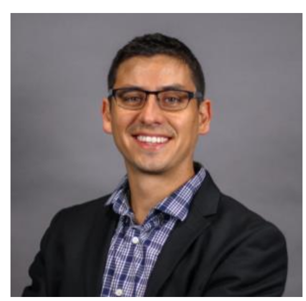
In this work, we apply resonant elastic x-ray scattering (REXS) in a grazing incidence configuration to extract the cross-sectional profile of patterned resists before they have been developed (*i.e.*, latent image). We will show how the difference in chemistry induced by the exposure and baking steps can produce enough scattering contrast at certain X-ray energies near a resonant absorption edge in order to provide a 3D latent image profile of the pattern with sub-nanometer resolution [1]. In one case, we explain how latent images were acquired on PMMA and CAR resists by applying REXS near the Carbon K-edge. The reconstruction of this profile provides morphological information that can be compared with the final profiles obtained after development, but the REXS chemical contrast mechanism itself may also shed insight into the chemical nature chain scission process. Altogether, this information may be used to shed light on the effect that various development and exposure conditions may have on the final roughness parameters that are critical to modern lithography. Finally, we will elaborate on the impact of the measurement itself (*i.e*. beam damage) on the resulting pattern morphology as well as how this approach may be applied across other types of resists.

[1] G. Freychet, I.A. Cordova, T. McAfee, D. Kumar, R.J. Pandolfi, C. Anderson, P. Naulleau, C. Wang, A. Hexemer, "*Using resonant soft x-ray scattering to image patterns on undeveloped resists*," SPIE 2018.

Presenting Author



Isvar A. Cordova has been a Postdoctoral Fellow at the Advanced Light Source (ALS) at Lawrence Berkeley National Lab (LBNL) working primarily at the resonant soft x-ray scattering beamline, but recently joined the Center for X-Ray Optics (CXRO) team focused on applying advanced scatterometry techniques to address EUV lithography needs. While at LBNL, Isvar has led an LDRD proposal which resulted in a provisional patent on a new x-ray scattering method to study material interfaces and worked with industry partners to develop a versatile vacuum-compatible instrument facilitating the *in-situ* study of samples under a variety of environments (i.e. liquid, gas, heating, and electrochemical). Given the fact that Isvar enjoys cultivating collaborations and working within highly multidisciplinary teams, he is motivated by the potential to expand the use of resonant scattering to fields that may not have taken full advantage of this technique, such as semiconductor metrology and time-resolved studies of buried interfaces.

Isvar earned his Master's and Ph.D. from Duke University's Electrical and Computer Engineering department with a focus on designing novel electrochemical electrode architectures by nanostructuring metal oxide coatings, holds a Physics (B.S.) degree from NCCU, and an Economics (B.A.) degree from UNC-Chapel Hill. In addition, Cordova designed and operated a custom-built hot wall atomic layer deposition system and coordinated a multidisciplinary "Scalable NanoManufacturing" research project sponsored by NSF focused on the integration of roll-to-roll processable organic photovoltaics and supercapacitor devices. Cordova is an author of 7 peer-reviewed articles and has presented his work at several domestic and international conferences spanning various fields. Since joining Berkeley Lab, he has been the primary author on 6 successful proposals, including one Laboratory Directed Research and Development (LDRD).

P32

Progress in EUV Resists Towards High-NA EUV Lithography

Xiaolong Wang[1], Zuhal Tasdemir[1], Michaela Vockenhuber[1], Iacopo Mochi[1], Lidia van Lent-Protasova[2], Marieke Meeuwissen[2], Rolf Custers[2], Gijsbert Rispens[2], Rik Hoefnagels[2], Yasin Ekinci[1]

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The semiconductor industry is planning to introduce extreme ultraviolet lithography (EUVL) into high volume manufacturing (HVM) at 7 nm node [1]. The most promising candidate High-NA EUVL with resolution of 8 nm half-pitch is going to outperform all the previous scanner although further development is needed [2]. Although record resolution half pitch (HP) 11 nm has been achieved with the current EUV resists [1, 3-5], it is obvious that it will be a great challenge to meet the increased specifications of EUV resists for the high-NA era. Here we present systematically study of around 150 different EUV resist and highlight the 6 best performance resists. The evaluation of the resists have been done with the EUV interference lithography (EUV-IL) tool at the Swiss Light Source (SLS) synchrotron facility in the Paul Scherrer Institute (PSI). In this work, we focus on the performance of resist at HP 16 nm and HP 14 nm line/space and show several candidates that have improved one or several aspects of the resolution, line width roughness and sensitivity (RLS) tradeoff. The results are encouraging but overcoming the RLS requirements for high-NA EUVL production still remains challenges in resists development. In this context, the PSI EUV-IL tool used in this work is an effective tool which can address the resolution range of high-NA EUVL, i.e. 13 nm to 8 nm half-pitch. The EUV-IL tool has provided and continues to provide an effective platform for academic and industrial research enabling the characterization and development of new resist materials before commercial EUV exposure tools become available.

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Presenting Author

Dr. Xiaolong Wang received his PhD in 2017 from EPFL (Switzerland) working on nanophotonics. He is currently doing his postdoc at Paul Scherrer Institute (Switzerland) since 2018. He is working on advanced lithography and nanofabrication. Also, he is working on the projects with EUV lithography industry.

P33

Multi-Trigger Resist (Invited)

G. O'Callaghan[a,b], C. Popescu[b], Y. Vesters[c,d], A. McClelland[b], J. Roth[e], W. Theis[f], A.P.G. Robinson[a,b]

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[b]School of Chemical Engineering, University of Birmingham, UK.
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[d]KU Leuven, Chemistry Department, Celestijnenlaan 200F, 3001 Leuven, BE
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[f]School of Physics and Astronomy, University of Birmingham, UK.

The development of a photoresist to support EUV lithography in high volume manufacturing for the next node and beyond remains a challenging issue, with no material currently meeting the combined resolution, sensitivity, and line width roughness (RLS) requirements, and additional stochastic defectivity issues yet to be addressed. Whilst traditional chemically amplified resists will likely support the initial insertion, a wide range of materials options are being examined for future nodes [1–3], aiming to identify a photoresist that simultaneously meets RLS and defectivity requirements.

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

The multi-trigger material previously presented [4, 5] consists of a base molecule and a crosslinker, which represent the resist matrix, together with a photoacid generator (PAG). MTR2 showed 16 nm half pitch lines patterned with a dose of 38 mJ/cm^2, giving a LER of 3.7 nm on the NXE3300 [4]. Since then, research has been undertaken to improve this resist. In particular we are focusing on improving resist opacity and present initial results for the MTR262Z(D) resist formulation here. Figure 1 shows semi-dense 15.8 nm CD lines patterned using the NXE EUV Scanner in MTR262Z(D) at a half pitch of 20nm, and dose of 13mJ/cm^2. Figure 2 shows lines with a CD of 12 nm patterned at 22.5 mJ/cm^2 on a 16 nm half pitch.

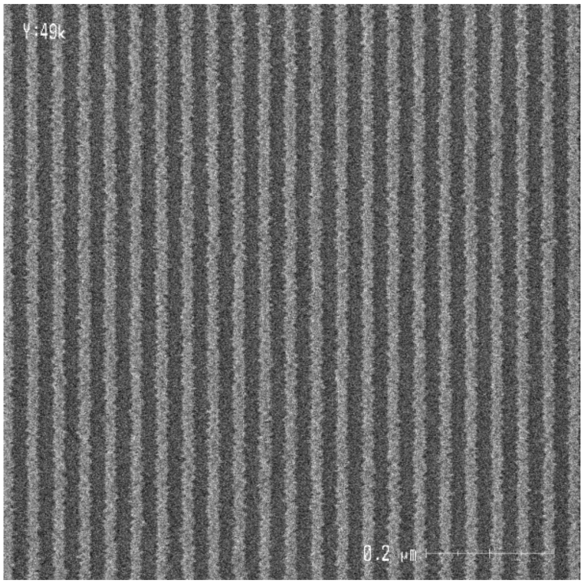

Figure 1

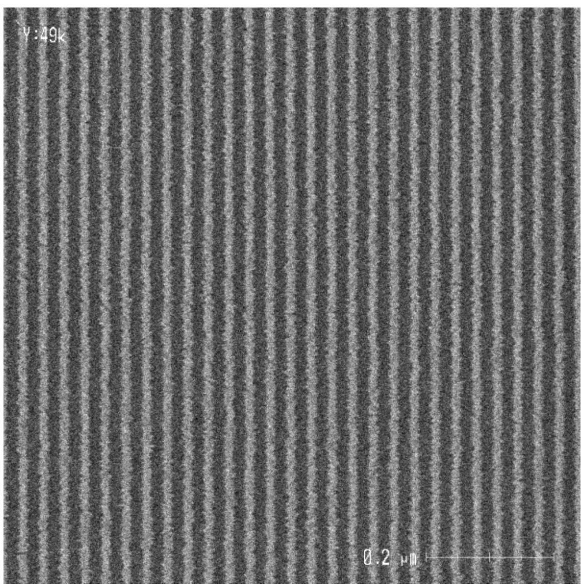

Figure 2

Figure 1 (Top): MTR262Z(D) (high opacity resist) Halfpitch 20nm, 13mJ/cm^2, CD 15.9nm, LER 6.7nm (biased). (Rectangular Scan.)

Figure 2 (Bottom): MTR262Z(D) (high opacity resist) Halfpitch 16nm, 22.5mJ/cm2, CD 12.2nm, LER 4.7 nm (biased). (Rectangular Scan.)

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Presenting Author

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

P34

EUV Resists: Can We Move Fast and Light? (Invited)

Anna Lio

Intel Corporation

Extreme Ultraviolet Lithography (EUVL) at 13.5 nm wavelength is getting implemented in High Volume Manufacturing (HVM). In this paper we assess the current status of EUV photoresists, some of the requirements that EUV photoresists will need to satisfy and propose a new paradigm for resist development in the near and long term future.

Presenting Author

Dr. Anna Lio is a 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.

P35

Role of Ambient Conditions on Organotin Cluster Based Extreme Ultraviolet Resist Chemistries

Gregory S. Herman, J. Trey Diulus, Ryan T. Frederick, Rafik Addou

School of Chemical, Biological, and Environmental Engineering, Oregon State University, Corvallis, OR, 97331, USA

Our recent efforts to study organotin compounds as extreme ultraviolet (EUV) resists have leveraged surface science approaches, where we have focused on characterizing both radiation and thermal induced processes. A benefit of organotin clusters as EUV resists is that they incorporate high absorption coefficient elements (e.g., Sn) and radiation sensitive ligands (e.g., buytl groups). In this presentation, we are investigating a butyl tin-oxo Keggin cluster-based model EUV photoresist. The goal of these studies are to better understand both surface chemistries and patterning mechanisms. The thermal and radiation induced chemistries indicate that butyl ligands are thermally stable up to ~650 K, but homolytic cleavage of the carbon-tin bond occurs during exposure to low kinetic energy electrons (E_{kin} = 80 eV). We have found that different ambient conditions and photon energies result in large differences in radiation induced reaction rates, where a significant enhancement in carbon decay was observed for O_2 pressures up to 1 torr. These studies provide a means to better understand radiation induced processes that result in the solubility contrast of these materials, and may guide in the development of improved EUV photoresists for nanolithography.

Presenting Author

GREGORY S. HERMAN received his B.S. degree in Chemistry at the University of Wisconsin-Parkside in 1985 and his PhD. in Physical Chemistry at the University of Hawaii at Manoa in 1992. Gregory has had positions at Pacific Northwest National Laboratory, Hewlett-Packard Corporation, and Sharp Laboratories of America. In 2009 he joined the School of Chemical, Biological and Environmental Engineering at Oregon State University (OSU) as an Associate Professor and is currently Professor, Head, and James and Shirley Kuse Chair in Chemical Engineering.

P41

EUV Metrology with a Compact Accelerator-based Source (Invited)

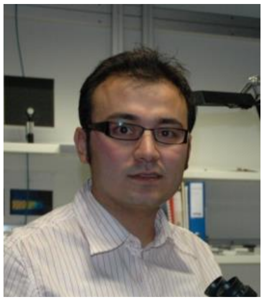
Yasin Ekinci

Paul Scherrer Institut, Switzerland

Actinic inspection and review on EUV masks are considered an essential tool for the EUV lithography. RESCAN (REflective-mode EUV mask SCANning microscope) is an actinic patterned mask metrology platform currently under development at Paul Scherrer Institute (PSI). It is a lensless microscope based on coherent diffraction imaging (CDI). In RESCAN, the sample is illuminated with a coherent EUV beam and the scattered beam is recorded by a pixel detector. Multiple diffraction patterns are combined together to reconstruct the sample image and phase. We believe that this a viable approach for mask review and inspection.

This method needs a coherent and high-brightness EUV source and currently, it uses the delivered by Swiss Light Source (SLS). One of the challenges is the availability of a source with high brightness, stability, and availability. I will present the design of a compact and accelerator-based light source producing EUV radiation with high-brightness for actinic metrology applications in the semiconductor industry. The design is based on the well-established components and design principles. Such a source can be used for actinic mask inspection, mask review as well as wafer metrology using CDI, conventional microscopy or scatterometry in the production environment, thanks to its stability, high-brightness, wavelength tunability, and relatively small footprint.

Presenting Author



Yasin Ekinci is head of the Advanced lithography and Metrology group and acting head of the Laboratory for Micro and Nanotechnology at Paul Scherrer Institute. He obtained his PhD in Max-Planck Institute for Dynamics and Self-Organization, Göttingen, Germany in 2003. He worked on various topics of nanoscience and technology, including atom optics, surface science, EUV lithography, resist materials, coherent scattering, lensless imaging, plasmonics, metamaterials, biosensing, semiconductor nanostructures, and nanofluidics. He is author/co-author of about 180 papers and 5 patent applications. He is a fellow of SPIE.

P42

Adlyte Corporation – Source Update (Tentative Title) (Invited)

Fariba Abhari

Adlyte Corporation, Switzerland

Adlyte has been developing a droplet based laser produced plasma (LPP) light over the last decade, specifically focused on the needs of actinic mask Blank and Patterned inspection as well as AIMS tools. Here, latest technical improvements in the EUV brightness and operational capability of the LPP light source will be presented. Having demonstrated brightness measurements of over 300 W/mm^2 sr, Adlyte's light source would fulfill all the technical requirements of actinic patterned mask inspection systems for the present and many future nodes, lowering technology risks for future upgrades. Long run time testing results will be presented. The small footprint of the source as well as state of the art platform damping technology ensures that the light source can be seamlessly integrated into the inspection tool.

In this talk, the current state of the source will be presented. Results from a range of performance tests will be shown. Importantly, the test results from a long term continuously operating will be presented as well as the improvements in the availability the source to above 90%. New modular design as well as new innovations in the debris mitigation will be shown to reduce the COO.

Presenting Author

Fariba Abhari has been in the semiconductor industry for the past 25 years, having held a number of senior management positions in technology, marketing and field support of semi Capex equipment at Lam Research, KLA Tencor, Ultratech, and Formfactor. She is a graduate of UC Berkeley in material science & engineering.

P43

Lithography Machine In-line Broadband Spectrum Metrology and Feedback-control System

Fei Liu[1], Dries Smeets[1], Sjoerd Huang[1], Andrei Yakunin[1], Peter Havermans[1], Rene Oesterholt[1], Muharrem Bayraktar[2], Fred Bijkerk[2]

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[2] Industrial Focus Group XUV Optics, MESA + Institute for Nanotechnology, University of Twente, The Netherlands

The Laser Produced Plasma (LPP) EUV source emits a broadband spectrum. In general, the spectrum other than in-band EUV is undesirable, since these wavelengths will cause pellicle, illuminator and projection optics heating, degrade imaging contrast and influence the quality of imaging.

We have developed a new concept for in-line broadband spectrum metrology and a feedback control system which enables in-line broadband spectrum measurements. It makes it possible to proactively track the drift in the DUV and IR radiation during the production to avoid pellicle break and imaging and overlay performance degradation. It also enables broadband spectrum optimization for pellicle, imaging and overlay performance, and it makes quick trouble shooting possible when the scanner imaging and overlay performance degrades.

Presenting Author

Fei Liu received his Ph.D. from University of California-Davis in 2013. His PhD research is on design and development of 100MW peak power TEA CO2 lasers. Afterwards he joined ASML research department working on feasibility study of alternative architecture of EUV LPP source. His current interest is EUV source-scanner integral system performance optimization. He received Richard Snavely Memorial Award in 2009.

P44

Challenge of High Power LPP-EUV Source with Long Collector Mirror Lifetime 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 actual collector mirror reflectivity degradation rate is less than 0.4%/Gp by using real collector mirror around 125W (at I/F clean) in burst power during 30 Billion pulses operation. Recently we have redefined target power higher >330W and its development plan[4)]. Also we will update latest challenges for >330W average operation with actual collector mirror at the conference.

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Presenting Author

Dr. Hakaru Mizoguchi is Exective Vice President and CTO of Gigaphoton Inc. He is a Fellow of The International Society of Optical Engineering (SPIE), and also 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 guest scientist of Max-Plank Institute Bio-Physikalish-Chemie in Goettingen in Germany 2 years, from 1988 to

1990. Since 1990 he concentrated on KrF, ArF excimer laser and F2 laser research and development for lithography application. He was general manager of research division in Komatsu Ltd. until 1999. He got Dr. degree in high power excimer laser field from Kyushu university in 1994. In 2000 Gigaphoton Inc. was founded. He was one of the founders of Gigaphoton Inc.. From 2002 to 2010 he organized EUV research group in EUVA program. Now he is promoting EUV light source product development with present position. He got Sakurai award from OITDA Japan in 2018.

P45

High Repetition Rate (81.25MHz) FEL Project Based on cERL

Hiroshi Kawata, Hiroshi Sakai, Norio Nakamura, and Ryukou Kato

High Energy Accelerator Research organization (KEK)

High repetition rate EUV-FEL based on ERL is one of the promising candidates for the future high power light source on next generation lithography. On the other hand, even at the mid infrared light source, there is no such high repetition rate and high power light source, in which the wave length is tunable.

Recently, we succeeded to get the competitive funding "new laser technology development for processing laser" from NEDO (New Energy and Industrial Technology Development Organization) for mid infrared FEL in cERL with 81.25 MHz repetition rate. We will realize the FEL by March of 2021. The full detail of the project will be presented at the workshop and also the relationship of the technical development between the present mid infrared FEL and EUV-FEL will be discussed.

Presenting Author

Prof. Dr. Hiroshi Kawata is with Department of Advanced Accelerator Technologies, HIgh Energy Accelerator Research Organization (KEK), Japan.

P46

Energetiq Source Update (Tentative Title) (Invited)

Toru Fujinami

Energetiq

Presenting Author

Toru Fujinami is the Sr. Director of Business Development at Energetiq.

P51

Thulium-based EUV Drive Lasers Scalable to Near-MW Average Powers (Invited)

C.W. Siders, S. Langer, A.C. Erlandson, T.C. Galvin, B.A. Reagan, E.F. Sistrunk, T.M. Spinka, and C. L. Haefner

Advanced Photon Technologies, Lawrence Livermore National Laboratory, NIF & Photon Science Directorate, 7000 East Avenue, Livermore CA 94550

Laser architectures based upon multi-pulse extraction and continuous-wave laser diode pumping are scalable to near-MW average power while maintaining application-enabling high peak power. These new high average power lasers are capable of producing up to 300kW average power and (for applications requiring ultrashort pulses) peta watt class peak powers and can provide highly tailorable pulse shapes optimized using machine learning. They utilize direct diode pumping of the amplifier medium with commercially-available, high-efficiency continuous-wave diodes to pump Tm:YLF solid-state gain media to achieve high efficiencies and cost effectiveness. We will discuss the Big Aperture Thulium (BAT) laser, a new class of high-power 2-µm laser, and present new results on laser architecture and anticipated performance for driving EUV sources usable for next-generation Blue-X photolithography.

Presenting Author

Dr. Siders is a physicist at Lawrence Livermore National Laboratory's National Ignition Facility (NIF) & Photon Science Directorate. As Program Leader for Laser-Driven Secondary Sources he fosters the growth of scientific and commercial LDSS opportunities within the Advanced Photon Technologies (APT) Program, and as Senior Scientist he engages in the evaluation and development of technologies towards future advanced photon sources and their applications. APT investigates and develops cutting-edge laser technologies that enable scientific advancement, Inertial Fusion Energy (IFE) relevant technologies, and new commercial applications. A Senior Member of the Optical Society of America, Dr. Siders has over 30 years of experience in optics, photonics, and high-intensity & high-energy density physics, including experience at the sister

National Laboratories of LLNL and Los Alamos (LANL) and his published work has garnered over 7000 citations. Before joining LLNL, he was an assistant professor of optics, photonics and physics at the College of Optics and Photonics/CREOL at the University of Central Florida (UCF) in Orlando. While there, he was a co-founder of a start-up fiber laser company. Craig's 1998-2000 work as a Research Faculty member in Kent Wilson's group at UCSD involved some of the earliest applications of femtosecond X-ray diffraction to the study of unique states of matter, with seminal publications in *Science* and *Nature*. His 1996 doctoral thesis work at UT Austin with Mike Downer and Toshi Tajima involved designing and building one of the earliest table-top Terawatt lasers and applying it to the first demonstration of a Laser Wakefield Accelerator. Craig graduated with Highest Honors and Distinction in Physics from Kenyon College in 1988.

P52

Advanced Multilayer Development for the Water-Window Spectral Region (Invited)

F. Delmotte, C. Burcklen**, E. Meltchakov, J. Rebellato, S. de Rossi

Laboratoire Charles Fabry, Institut d'Optique Graduate School, CNRS, Universite Paris-Saclay, 91127 Palaiseau Cedex, France
*** current affiliation: Lawrence Livermore National Laboratory, Livermore, California, USA*

The Laboratory Charles Fabry (LCF) has been a pioneer of EUV/x-ray interference coating research since the early 70s [1]. Most notable achievements include the Nevot-Croce interfacial roughness model and the development of multilayer coatings for the Extreme ultraviolet Imaging Telescope (SOHO/EIT), the first satellite solar mission launched in 1995. LCF also prepared the multilayer optics for the EUV telescopes of the NASA's STEREO mission (2006), and of the ESA Solar Orbiter mission, to be launched in 2020. LCF researchers were the first to achieve a significant increase of the measured reflectance by adding a 3rd material in a periodic multilayer structure [2]. Recently, LCF researchers reported experimental reflectance of 58% at wavelengths near the Al L2,3 edge (17 nm) with a new 3-material multilayer (Al/Mo/SiC) [3].

Cr/Sc-based multilayers for the water window (284 eV-543 eV) have been studied and developed by several laboratories for a wide range of applications during the last 20 years. Nevertheless, the experimental reflectance is still far from the theoretical value, mainly due to the drastic influence of interfacial imperfections. Indeed, a periodic Cr/Sc stack with a period thickness as low as 1.6 nm and a repetition number of several hundred periods is required in order to reflect efficiently x-rays below the Sc-L2,3 edge (~399 eV) and the experimentally achievable peak reflectance depends primary on the smoothness of interfaces. We have recently shown that the nitridation of Cr layers in Cr/Sc interference coatings induces a significant increase of peak reflectance [4]. We have also demonstrated that the addition of B_4C layers at the Sc-on-Cr interfaces of a Cr/Sc multilayer improves the reflectance. Recent results obtained by combining these two effects will be presented and discussed.

The authors would like to thank D. Dennetiere, B. Capitanio and F. Polack at SOLEIL for their assistance during the synchrotron measurements. The multilayers were deposited with support from CEMOX, a platform of LUMAT federation (CNRS FR2764). This work was supported by the French Research Agency (project n° ANR-11-EQPX-0029).

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Presenting Author

Franck Delmotte obtained a Ph.D. in Electrical Engineering at the University Paris-Sud (Orsay, France) in 1998. He is currently Professor at the Institut d'Optique Graduate School where he is teaching Optical Thin Films and X-ray Optics. Head of the XUV Optics Group at Laboratoire Charles Fabry, his main research interests consist of interference coatings for extreme ultraviolet (EUV) and x-ray applications including EUV telescopes for space science, x-ray diagnostics for laser plasma experiments (Laser Mega Joule), optical components for attosecond pulses and free electron lasers, multilayer gratings for synchrotron radiation. He is currently Co-Investigator of the Extreme UV Imagers consortium for the Solar Orbiter ESA mission, in charge of the development and delivery of mirrors and coatings for the two EUV telescopes.

P53

An Optimization Study of EUV Sources Driven by Lasers of Different Wavelengths (Invited)

Steven Langer, Howard Scott, and Craig Siders

Lawrence Livermore National Laboratory

Merlin is a workflow framework that is under development at LLNL. We use Merlin to run ensembles of HYDRA simulations of laser-heated tin vapor targets. Merlin allows us to automate the process of finding an optimal laser pulse and tin density for a laser of a given wavelength. This automated approach makes much more efficient use of a scientist's time than running many simulations manually and makes it viable to study more target parameters and a wider variety of lasers. Our study optimizes EUV emission into the 13.5 nm bandpass for 10.6 μm CO_2 and 1.9 μm thulium lasers. The target is a uniform density cylinder of tin vapor. This simplified target allows us to use (fast) 1D HYDRA simulations so that we can afford to run several ensembles for each laser. Some of the parameters to be varied include the laser intensity and pulse duration and the target density and thickness. If there is time, we will also vary the pulse shape for the thulium laser to assess whether pulse shaping helps improve the EUV conversion efficiency. 2D simulations can be run in future ensembles to obtain a more refined estimate in the region that
has the best CE in the 1D simulations.

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Presenting Author

Howard Scott is a staff physicist at Lawrence Livermore National Laboratory where he has been developing simulation codes since 1986. He holds a PhD in astrophysics and has worked in the areas of inertial confinement fusion, magnetic fusion energy, X-ray lasers, nuclear weapons, and even some astrophysics. His particular research interests are radiation transport, non-LTE physics, plasma spectroscopy and large-scale simulations.

P54

Refractive Index Measurements with Improved Accuracy Around EUV/x-ray Absorption-edges and Impact in Multilayer Modeling (Invited)

Regina Soufli[1*], Franck Delmotte[2], Farhad Salmassi[3], Julia Meyer-Ilse[3], Catherine Burcklen[1], Jennifer Rebellato[2], Nicolai Brejnholt[1], Sonny Massahi[4], David Girou[4], Finn Christensen[4], Eric M. Gullikson

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Precise knowledge of the wavelength-dependent, complex refractive index (optical constants) of materials is required to accurately design, build and calibrate instruments in the EUV/x-ray range. Such instruments include imagers, microscopes and spectrometers for photolithography, plasma physics, synchrotron and laser science and space-borne telescopes for solar physics and astrophysics. Yet, optical constants values in the EUV/x-ray are often unreliable. This is due to the extreme sensitivity of materials to contamination and oxidation in the EUV, to the difficulty in fabricating appropriate thin film samples, to the presence of near-edge absorption fine structure, and to multiple reflections present at the longer EUV wavelengths, which are complicating the measurements. We are presenting a new set of measurements and a self-consistent determination of the optical constants of Cr, W and Pt thin films. We use a combination of photoabsorption and reflectance data in the photon energy range 25 - 800 eV which includes the L- and M-shell absorption edges of Cr and the N- and O-shell absorption edges of W and Pt. Our experimental data demonstrate for the first time highly resolved fine structure in the region of the Cr $M_{2,3}$ and $L_{2,3}$ edges, the W $N_{4,5}$ and $N_{2,3}$ edges and the Pt $O_{2,3}$, $N_{6,7}$ and $N_{2,3}$ edges in both the absorptive and dispersive portions of the refractive index, resulting in differences of up to a factor of 3 compared to optical constant values published earlier. The improved accuracy of the new optical constants is validated via "sum rule" tests and by simulating experimental reflectance data of single-layer and multilayer coatings containing these materials [1-4]. The implications of these new results, as well as plans for future work, will also be discussed.

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Presenting Author

Regina Soufli received her Ph.D. in Electrical Engineering from the University of California, Berkeley. Her interests are in extreme ultraviolet (EUV)/x-ray interactions with matter, surface and materials science, multilayer thin films, and x-ray optics. She was staff scientist at the Harvard-Smithsonian Center for Astrophysics, working on NASA's Chandra X-ray Observatory. At Lawrence Livermore National Lab she has led programs related to EUV/x-ray optics for photolithography, solar physics and astrophysics, synchrotron and free-electron lasers, and high-energy physics. She has invented corrosion-resistant EUV multilayer coatings and has developed x-ray optics for the LCLS free-electron laser, EUV multilayer optics for NASA's Solar Dynamics Observatory, for the GOES space weather satellites and for the Micro-Exposure Tool-5, the first EUV camera with a numerical aperture of 0.5. She is author of over 130 publications and has received two "R&D 100" awards. She is a Fellow of the Optical Society (OSA) and a Senior Member of SPIE.

P55

Characterization of Laser-produced Plasmas in the 1-6 nm Region using Cryogenic Xe Targets

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We present measurements from laser-produced plasmas generated from cryogenic Xe targets and quantify the emission characteristics for EUV radiation production. The system is based on a LN2-cooled rotating drum, which allows for high repetition rate, and a Nd:YAG laser system with energies up to 300mJ with pulse lengths 130-600ps at 1064nm. High resolution spectra are measured in the 1-6nm range for the first time with this system, and high conversion efficiencies at wavelengths down to 1.4nm are measured. In addition, the emission spot size is directly measured using a slit imaging method, which shows optimized emission spot sizes <20□m in the 2nm range (Fe band). Faraday cup analysis of the low energy ion spectrum allows an estimation of the plasma temperature, which shows some scaling with laser parameters.

Presenting Author

Simon C. Bott-Suzuki received the M.Phys. (1999) and Ph.D. (2004) degrees in Physics from Sheffield University, U.K., before carrying out post-doctoral research at Imperial College London. He moved to the Center for Energy Research, University of California San Diego in 2006, where he is presently an Associate Research Scientist. He is also a Visiting Professor at Cornell University. He specializes in the experimental analysis of plasmas generated using pulsed power techniques and their application in inertial fusion, basic plasma physics and laboratory astrophysics. He has published over 60 journal papers, and served as the co-Chair of the 9th International Conference on Dense Z-Pinches (Napa, CA 2014). He has also served in various roles for the ICOPS conference series and as Guest Editor for the Fourth and Fifth Special Issues on Z-Pinch Plasmas published in the IEEE Transactions on Plasma Science.

P56

Effect of Laser Wavelength on EUV Plasma Dynamics, Source Efficiency, and Ionic Debris Evolution (Invited)

Tatyana Sizyuk

Center for Materials under Extreme Environment (CMUXE)
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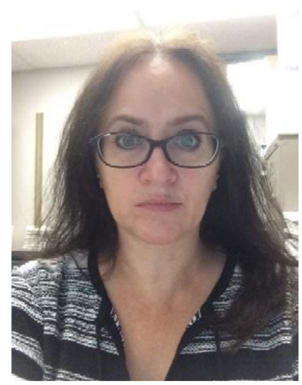
The efficiency of EUV source depends on the optimization of laser parameters in parallel with target size and geometry. The laser wavelength can play significant role in this regard. Previous experiments and our comprehensive integrated modeling showed that the conversion efficiency (CE) of EUV source produced by single CO2 laser from small droplet is very low, approximately 5 times less that the efficiency of the source produced by this laser from planar target. However, this laser allows significant improvement of the CE when the dual-pulse technique is used. The efficiency of sources produced by Nd:YAG laser is less affected by the target geometry. However, not much significant optimization of EUV sources can currently be achieved in dual-beam scheme consisted of two Nd:YAG lasers in comparison with the combination of Nd:YAG and CO2. More innovations in this area are needed. Further studies are required to determine the effect of laser wavelength in the range between 1.064 μm and 10.64 μm on the source efficiency.

We investigated in detail the difference in laser produced plasma evolution and ion debris characteristics using single and dual lasers with various wavelengths and the resulting EUV conversion efficiency using our full 3D comprehensive HEIGHTS simulation package.

Presenting Author



Prof. Tatyana Sizyuk is the Associate Director of the Center for Materials under Extreme Environment (CMUXE) at the School of Nuclear Engineering, Purdue University. She developed and optimized several models and parallel algorithms implemented in our 3D multi-physics HEIGHTS package for the simulation of LPPs for EUV Lithography, WaterWindow (WW) microscopy, LIBS, and colliding plasma experiments. She studied in details laser produced plasma with wide range of characteristics regarding the EUV sources optimization and debris mitigation. Her research interests also include modeling and analysis of plasma facing materials in fusion reactor, development of predictive modeling through the benchmarking with in-house and worldwide experiments. Her research results were published in many journal articles and presented at vrious conferences and workshops related to photon sources in LPPs, plasma/material interactions, fusion reactor development.

P57

Adaptation of the Reflectance of Bragg Mirrors to Wide Source Spectra (Invited)

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In the EUV the spectrum of the widely used CO2 laser produced Sn plasma source is wider than that of the standard Bragg mirror. The mismatch is more apparent in the sub-10nm domain where, due to the lower index contrast, the reflectance spectra of the Bragg mirrors are sharper and the source spectra are often even wider [e.g. P. Dunne et al., www.euvlitho.com/2018/S44.pdf].

In this numerical study we modify Bragg mirrors by introducing grading, i.e., by modifying the thicknesses from layer to layer (linear increase from top to bottom). With higher grading factor (thickness ratio of thickest to thinnest bilayer) the spectral and angular widths increase but the peak reflectance decreases. In order to take into account the spectral widths of source spectra the broadened reflection peaks of Mo/Si (peak position 13.5 nm), La/B4C (6.64 nm) and Cr/Sc (3.12 nm) are weighted by those of Sn, Tb and Gd, and Bi, respectively. The weighted reflectance spectra demonstrate that the graded mirrors in comparison to ungraded mirrors allow exploiting more total power of a source.

Presenting Author

Professor Meisels studied physics at the University of Vienna, Austria from 1974. From 1997 he worked on his dissertational thesis "Spectroscopy of III-V Compounds in the Far Infrared" and acquired his PhD in 1983. He worked as a post doc until 1993 with a research stay at the Imperial College in London in 1987 - 1988. Then he worked as a university assistant at the Montanuniversitaet in Leoben until 2002 when he completed his habilitation. Since then he is associate professor at the Montnuniversitaet.

P61

Achieving Diffraction-limited Performance on the Berkeley MET5

Ryan Miyakawa

CXRO

The Berkeley MET5, funded by EUREKA, is a 0.5-NA EUV projection lithography tool located at the Advanced Light Source at Berkeley National Lab. Wavefront measurements of the MET5 optic have been performed using a custom in-situ lateral shearing interferometer suitable for high-NA interferometry. In this paper, we report on the most recent characterization of the MET5 optic demonstrating an RMS wavefront 0.31 nm, and discuss the specialized mask patterns, gratings, and illumination geometries that were employed to accommodate the many challenges associated with high-NA EUV interferometry.

Presenting Author

P62

A SHARP tool for current and future nodes of EUV lithography

Markus Benk, Ryan Miyakawa, Patrick Naulleau

CXRO

The Sharp High numerical aperture Actinic Reticle review Project (SHARP) is a synchrotron-based, extreme ultraviolet (EUV) microscope dedicated to photomask research. SHARP emulates the mask-side numerical aperture, imaging conditions and illumination settings of current and future EUV lithography scanners. The tool uses Fresnel zoneplate lenses as imaging optics. With 100s of lenses installed in the tool, the user can select a variety of mask-side numerical apertures. SHARP's lossless Fourier-Synthesis illuminator produces arbitrary pupil fills, including pixelated sources, gray-scale sources and sources with a low fill factor and correspondingly high spatial coherence. Owing to its versatile architecture, SHARP has applications both in process development and advanced photomask research.
SHARP emulates the FlexPupil illuminators of the NXE:33x0 and NXE:3400 scanners to support process development for the 0.33-NA generation of EUV lithography. A throughput of up to 24 sites per hour, automated mask-loading from RSP200 SMIF pods and navigation at 2-µm position accuracy (4x) enable defect imaging, printability assessment and repair verification on production-level photomasks.

To support research towards high-NA EUV lithography, we have demonstrated the emulation of anamorphic imaging on the SHARP microscope. User experiments at 0.55 4x/8xNA and 6º chief-ray angle have produced encouraging results and provided valuable data on the performance of such imaging systems. New zoneplates matching the EXE:5000 scanner with a reduced chief-ray angle of 5.355º and central obscuration are currently in production and will be available soon.

The paper provides an overview of the SHARP microscope and its key components. Various application examples are presented, discussing both the 0.33-NA and 0.55-NA generation of EUV lithography.

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

Presenting Author

P63

Measuring Chemical Image in Photoresist

Luke Long

CXRO

Previous modeling work with multivariate Poisson propagation model (MPPM) has shown that photodecomposable base has the potential to improve the RLS performance of chemically amplified resist. The model suggests the improvement comes from the ability to build steeper chemical gradients at lower dose than can be achieved with conventional quencher, and that this slope leads to improved line edge roughness. A critical question is whether the relationship between photodecomposable base, chemical slope, and line edge roughness can be verified experimentally. Here we present on the potential of resonant soft X-ray scattering (RSoXS) to probe the chemical image of exposed photoresist prior to development. During post-exposure bake of chemically amplified resist, the reaction of photoacid and polymer protecting group spatially changes the effective electron densities of the polymer in accordance with the exposure pattern. The result is a chemical diffraction grating that can be studied via scattering using soft X-rays tuned to be resonant with the particular changes in effective electron density. The energy-dependent diffraction pattern produced by the grating can be used to reconstruct the underlying deprotection image. The chemical slope can then be extracted and compared with the LER of the developed photoresist. Ultimately, the results will serve as a check on the MPPM, verify the connection between chemical gradient and LER, and provide key insights into photoresist LER mitigation strategies.

Presenting Author

P64

Quantitative Phase Imaging for EUV Photomasks

Stuart Sherwin

CXRO

EUV absorbers impart both attenuation and phase-shift onto the reflected electric field, impacting the image contrast and sensitivity to aberrations. Therefore, accurate characterization of the reflected complex field is critical to achieve the best image quality. In this work, we present several hardware and software approaches currently being explored at CXRO to precisely and robustly measure this reflected complex field.

Presenting Author

P65

Photoemission Study on EUV Materials

Jonathan Ma, Andrew Neureuther, Patrick Naulleau

CXRO

Chemistry in EUV resist is fundamentally different from DUV. Photon induced chemistry in UV resists is specific and direct, thus well understood. In EUV, however, chemistry is driven by secondary electrons, giving rise to fundamental questions about the chemical mechanisms. The primary electron energy affects the electron blur, while the electrons in the secondary background are hypothesized to drive chemistry. To Understand these electrons, condensed phase photoemission experiments are carried out to give information about both. Results on photoresists and underlayers will be discussed. The relationship between internal electron spectrum and photoemission spectrum will be discussed as well.

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Presenting Author

P66

Measurement of Electron Blur

Oleg Kostko, Jonathan Ma, and Patrick Naulleau

Chemical Sciences/Advanced Light Source, LBL

EUV photon absorption by a resist film leads to emission of a photoelectron and several low kinetic energy secondary electrons. The "universal curve", used in X-ray photoelectron spectroscopy, suggests that the low kinetic energy electrons may travel tens to hundreds of nanometers in solids until they inelastically scatter. The fact that electrons travel long distances before they may initiate chemical reactions ultimately result in blur of the aerial image, reducing the contrast and subsequently resolution of the resist. We will present an approach to experimentally determine distances that the emitted electrons travel in the resist material, which we define as the electron blur. Possibilities to gain additional information on electron penetration depth in resist films will also be discussed.

Presenting Author

P67

Assessing the Impact of Latent Imaging of Resists via Grazing Incidence Resonant X-ray Scattering

Isvar. A. Cordova[1,2], Guillaume Freychet [1,4], Scott. D. Dhuey[3], Alex Hexemer[1], Cheng Wang[1], Patrick Naulleau[3]

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In this work, we apply resonant elastic x-ray scattering (REXS) in a grazing incidence configuration to extract the cross-sectional profile of patterned resists before they have been developed (i.e., latent image). We will show how the difference in chemistry induced by the exposure and baking steps can produce enough scattering contrast at certain X-ray energies near a resonant absorption edge in order to provide a 3D latent image profile of the pattern with sub-nanometer resolution [1]. In one case, we explain how latent images were acquired on PMMA and CAR resists by applying REXS near the Carbon K-edge. The reconstruction of this profile provides morphological information that can be compared with the final profiles obtained after development, but the REXS chemical contrast mechanism itself may also shed insight into the chemical nature chain scission process. Altogether, this information may be used to shed light on the effect that various development and exposure conditions may have on the final roughness parameters that are critical to modern lithography. Finally, we will elaborate on the impact of the measurement itself (i.e. beam damage) on the resulting pattern morphology as well as how this approach may be applied across other types of resists.

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Presenting Author

P68

Gentle High Speed Atomic Force Microscopy using Encased Cantilevers and Spiral Scanning

Paul Ashby

Molecular Foundry

Scanned Probe Microscopy excels at nondestructively probing samples in-situ with high resolution. However, it has been plagued with very poor temporal resolution and insufficient spatial resolution to probe molecular details when operating in liquid. In my group we have extended the boundaries of SPM characterization by developing new probes for liquid environments that give an order of magnitude higher sensitivity. Encased cantilevers use a hydrophobic encasement to trap an air bubble around the cantilever and reduce damping while keeping the sample hydrated increasing sensitivity and resolution. We have also developed spiral scan algorithms that enable higher frame rates on large scanners providing the flexibility of large scan areas with near video rate imaging speeds.

Presenting Author

P69

Fundamental Dynamics of Bond-selective Chemistry Initiated by Low-energy Electrons (P69)

Dan Slaughter[1], Ali Belkacem[1] and Tom Rescigno[1], Cynthia Trevisan[2], C. William McCurdy[3]

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Low-energy electron-molecule resonances are partly accountable for chemical processes such as damage by ionizing radiation and the solubility of photoresist materials after extreme ultraviolet exposure[1,2]. Controlling these processes demands a detailed understanding of the underlying electron-molecule collisions including dissociative electron attachment (DEA). Resonant interactions between low-energy electrons and molecules can efficiently convert electronic energy into nuclear degrees of freedom, leading to vibrational excitation, isomerization or dissociation into reactive species. DEA can produce neutral and ionic products with a remarkably strong site-specificity on low energy electron energy. A detailed understanding of the underlying dynamics of DEA enables specific mechanisms to be described on the energy deposition by ionizing radiation, and the subsequent chemistry involving secondary electrons.

Anion fragment momentum imaging experiments and ab initio electron scattering theory are employed to interrogate the fundamental chemical dynamics of electron attachment to molecules in the gas phase. New results will be presented for formic acid, on the remarkable site-selectivity in hydride anion loss from the formyl or hydroxyl sites for this simple organic acid. We illustrate the relevance to materials processing in analyzing the complete energy transfer from a low energy electron into kinetic energy of dissociation and internal excitation of the products.

Work supported by the Office of Science, Office of Basic Energy Sciences, Division of Chemical Sciences, Geosciences and Biosciences of the U S Department of Energy.

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Presenting Author

P70

Alkyltin Keggin clusters as photoresist material for EUV Lithography

Rebecca Stern

UC-Berkeley

The challenges with using polymer-based photoresists for EUV lithography can be eliminated by using oxohydroxo metal nanoparticle photoresists instead. Oxohydroxo metal clusters have the potential to provide faster writing speeds, higher resolutions, and better etch resistance than chemically amplified polymer resists. The Persson Group at UC Berkeley, in collaboration with Oregon State University, conducted research on the stability of organotin Keggin clusters for use as sensitive high-resolution photolithographic resists. The sodium centered tin Keggin ions were synthesized and characterized, as well as computationally modeled. A one-step synthesis obtained the β-isomer (β-NaSn12), the γ-isomer (γ-NaSn12), and a γ-isomer capped with a butyltin (γ-NaSn13). The Sn Keggin ions crystallized readily without counterions which increased the simplicity of the synthesis as well as improved the yield, purity, and reproducibility. Solution characterization (SAXS, NMR, ESI-MS) verified that solutions contained only the Na-centered dodecamers. Computational modeling was used to determine the ground state electronic structure of these three butyltin Keggin structures, as well as the capped β-isomer (β-NaSn13), and the hypothetical α-isomers (α-NaSn12 and α-NaSn13). Computational modeling using density functional theory (DFT) to obtain the hydrolysis Gibbs free energy and HOMO-LUMO gap gave the stability ranking: β-NaSn12 > γ-NaSn12 > α-NaSn12 which was consistent which experimental observations. The uncapped isomers were computationally evaluated to be more stable than their respective capped analogues. There is a balance between corner-linking to minimize cation-cation repulsion, and edge-lining to maximize stability via bond formation. Therefore, this sodium centered tin Keggin ion represents the only Keggin ion family so far, that favors the isomers of lower symmetry. And finally, the system's neutral charge makes it a valuable model system for understanding the fundamental patterning mechanisms at play.

Presenting Author

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