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Workshop Abstracts

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Abstracts

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P1

EUV Lithography at the Threshold of High Volume Manufacturing (Keynote Presentation)

Harry J. Levinson

GLOBALFOUNDRIES, Santa Clara, CA

After decades of research and development, EUV lithography is poised for use in high volume manufacturing (HVM). For the first generation of manufacturing in which EUV lithography will be used, engineers are focused on practical issues, such as equipment reliability and productivity, mask defectivity, overlay, and wafer yield. Improvements are needed to have wafer costs using EUV lithography that are no higher than achieved with optical immersion triple patterning. Looking ahead to second generation EUV lithography, technology complexity increases significantly. For example, OPC will need to account for multiple consequences of mask 3D phenomena, affecting pattern placement as well as critical dimension control. Resist stochastic effects currently limit the resolution capability of EUV lithography. The extension of EUV lithography will require higher exposure doses to reduce these stochastic effects, but with attendant impact on productivity and process control. In spite of challenges, foundational capabilities with EUV lithography have been established, and we have potential for enabling the continued scaling of integrated circuits.

Presenting Author

Harry J. Levinson is Sr. Director of GLOBALFOUNDRIES's Strategic Lithography Technology organization and Sr. Fellow. Dr. Levinson also served for several years as the chairman of the USA Lithography Technology Working Group that participated in the generation of the lithography chapter of the International Technology Roadmap for Semiconductors. He is the author of two books, *Lithography Process Control* and *Principles of Lithography*. He holds over 60 US patents. Dr. Levinson is an SPIE Fellow, previously chaired the SPIE Publications Committee, and served on SPIE's Board of Directors. He has a BS in engineering from Cornell University and a PhD in physics from the University of Pennsylvania. His PhD thesis, titled *Resonances and Collective Effects in Photoemission*, addressed certain phenomenon involving the interactions of light and matter. For this work he received the Wayne B. Nottingham Prize in surface science.

P2

Compact, Bright, Plasma-based EUV Lasers for Metrology (Keynote Presentation)

Jorge. J. Rocca

Colorado State University, Fort Collins, CO

Metrology for semiconductor circuit manufacturing requires bright sources of EUV radiation. Compact plasma-based EUV lasers produce bright beams of EUV light from amplification in atomic transitions. These compact atomic lasers are characterized by a high brightness, narrow line width, and high average power. Advances in diode-pumped optical lasers are now allowing EUV lasers based on laser-created plasmas to operate at new heights in repetition rate and average power in the 10-20 nm wavelength region. At longer wavelengths, new interest in metrology at 47 nm fits well the unique capabilities of compact discharge-driven EUV lasers based on fast discharge excitation of an argon-filled capillary channel, which produce beams with tailored degree of coherence and unsurpassed average power. These lasers are now commercially available. Application of EUV lasers to nano-scale imaging, including inspection of lithography masks, atomic, molecular composition imaging with sub-100 nm resolution, and error-free nano-patterning will be reviewed.

Presenting Author

of Electrical and Computer Engineering and the Department of Physics at Colorado State University. His research interests are in the physics and development of compact EUV/soft-ray lasers and their applications, the development of high power lasers, and the study of high power laser interactions with matter, in particular with the goal of creating bright EUV/x-ray sources. His group is known for leading contributions to the development of bright table-top soft x-ray lasers, including the demonstration of the first table-top soft x-ray laser, and their application in several fields. Recently his group demonstrated the highest energy diode-pumped ultra-short pulse laser at 500 Hz repetition rate, and used it to demonstrate table-top soft x-ray lasers operating at increased repetition rates. He has published more than 250 peer-review journal articles in these topics that have accumulated more than 12,000 citations. Prof. Rocca received the Arthur. L. Schawlow Prize in Laser Science from the American Physical Society in 2011, and the Willis Lamb Prize for Laser Science and Quantum Optics in 2012. He is a Fellow of the American Physical Society, the Optical Society of America, and the IEEE. He also received an IEEE LEOS Distinguished Lecturer Award. Early in his career he was an NSF Presidential Young Investigator.

P3

Continued Scaling in Semiconductor Manufacturing with Extreme-UV Lithography
(Keynote Presentation)

Anthony Yen

ASML

As EUV lithography goes into high-volume manufacturing in 2019, the focus of the lithography community is shifting from "if and when" to "how well" EUV will enable the continued scaling of integrated circuits. For semiconductor manufacturing with EUV lithography beyond the first generation, several fundamental topics are being addressed to enable single-patterning EUV lithography at lower k1 values. Such topics include resolution and etch-resistance of the photoresist, the stochastic nature of the photon-resist interaction, the three-dimensional nature of the photomask, the mask-side non-telecentricity of the reflective imaging optics, etc. Mitigation of the side effects produced by the aforementioned aspects of the EUV lithography will allow it to extend into the initial years of the next decade with minimal use of double patterning. Minimization of these effects is also essential for the adoption of the high-NA (0.55) EUV exposure system, which is presently under development at ASML and whose goal is to enable EUV lithography to provide continued scaling in semiconductor manufacturing well into the next decade.

Presenting Author

Anthony (Tony) Yen is ASML's VP and Head of Technology Development Centers Worldwide. Prior to the current position, he was with TSMC (2006 – 2017) where he led the development of EUV lithography, including its mask technology, for high-volume manufacturing. Earlier in his career, he was a researcher with Texas Instruments (1991 – 1997) where he worked on various techniques, including early work on optical proximity correction, to enhance the practical resolution of microlithography. From 1997 to 2003, he was with TSMC where he led the group that developed lithography processes for TSMC's 0.25, 0.18, 0.15, and 0.13 micron generations of logic integrated circuits and then co-led infrastructure building for next-generation lithography technologies at SEMATECH. From 2003 to 2006 he was with Cymer where he headed its marketing organization. Tony graduated from Purdue University with a BS degree in electrical engineering and furthered his education at MIT, earning his SM, EE, PhD, and MBA degrees there. He has over 100 US patents and 90 publications. He is a fellow of SPIE and of IEEE.

P4

Current status, Challenges and Outlook of EUV lithography for High Volume Manufacturing (HVM)

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). Recently, significant progress has been made 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 mask blank defectivity, pellicle membrane manufacturing, and EUV photoresist materials. This presentation reviews the current status and challenges of EUV lithography for High Volume Manufacturing (HVM) as well as expectations for the next generation node.

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.

P5

Fundamentals of PSCAR and Overcoming the Stochastics Problems of EUV Lithography

Seiichi Tagawa

Institute of Scientific and Industrial Research, Osaka University

In EUV lithography, the most critical issue was low intensity of EUV light source for a long time. Now EUV light source power is at 250 W. The most critical problem for HVM with EUV lithography is the stochastics problems. The light source intensity and the resist sensitivity are complementary each other. 250 W EUV light source and 20 mJ/cm^2 EUV resists were required for HVM with EUV lithography. However, EUV lithography using 20 mJ/cm^2 EUV resist cannot provide enough of a process window by stochastics problems such as micro-bridges or line-breaks of lines and spaces (missing or kissing contact holes). No good solutions for stochastics problems have been reported.

The present keynote presentation shows two topics. The first topic is fundamentals of PSCAR and some improvement of stochastics problems by PSCAR. The second topic is the solution of both very high resist sensitization and overcoming stochastics problems of EUV lithography patterning such as micro-bridges or line-breaks of lines and spaces (missing or kissing contact holes). The new solution is introduced based on basic science of lithographic processes of resist materials but from the very different viewpoints of current lithographic way of dealing with stochastics problems. The new solution is robust properties and response with respect to random noise. The new solution can be applied to several generations of EUV lithography, although stochastics problems become more severe with higher resolution patterning of conventional chemically amplified resists.

Presenting Author

Seiichi Tagawa is special appointed professor (full time) of The Institute of Scientific and Industrial Research (ISIR), Osaka University. His principal research area is radiation chemistry and physics, ultrafast time resolved spectroscopy on radiation processes, polymer science, and EUV/EB and ArF/KrF resist processes and materials, especially fundamental research and new EUV/EB lithographic processes and materials. He received BS, MS, and PhD degrees in nuclear engineering from the University of Tokyo in 1969, 1971, and 1977, respectively. He had been assistant and associated professor of Univ. Tokyo and full professor of Osaka Univ., then emeritus professor and special appointed professor of ISIR, Osaka University since 2009 and then graduate school of Engineering, Osaka Univ. since 2013 and again ISIR, Osaka Univ. since 2017.

P11

High Power LPP-EUV Source with Long Collector Mirror Lifetime for Semiconductor High Volume Manufacturing

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We have been developing 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 such as; combination of pulsed CO_2 laser and Sn droplets, dual wavelength laser pulses shooting and mitigation with magnetic field have been developed in Gigaphoton Inc.. We have developed first practical source for HVM; "GL200E" 1) in 2014. We have proved high average power CO2 laser more than 20kW at output power cooperate with Mitsubishi electric cooperation2). Pilot#1 is up running and its demonstrates HVM capability; EUV power recorded at111W average (117W in burst stabilized, 95% duty) with 5% conversion efficiency for 22hours operation in October 20163). Availability is potentially achievable at 89% (2weeks average), also superior magnetic mitigation has demonstrated promising mirror degradation rate (= 0.5%/Gp) above 100W level operation with dummy mirror test.4).

Recently we have demonstrated actual collector mirror reflectivity degradation rate is less than -0.4%/Gp by using real collector mirror around 100W (at I/F clean) in burst power during 30 Billion pulses operation. We will report latest data at workshop.

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Presenting Author

Hakaru Mizoguchi is Executive Vice President and CTO Of Gigaphoton Inc. He is a member of The International Society of Optical Engineering, 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 his present position.

P12

Simulating EUV Emission from Laser-Produced Plasma

Steven Langer, Howard Scott, and Hai Le

Lawrence Livermore National Laboratory, Livermore, CA, USA

Radiation-hydrodynamics simulations of radiative emission from laser-produced plasmas require modeling hydrodynamics, laser propagation and absorption, heat conduction, radiation transport, and atomic kinetics. Basic temperature and density spatial scales follow from the laser parameters and material properties. EUV emission has a strong impact on the energy balance in the plasma, so it is necessary to have an accurate inline model for the non-LTE EUV opacity and emissivity. Our previous work [1] used inline atomic models with roughly 1000 configurations. We are currently modifying our code to use the Nvidia GPU boards on LLNL's new Sierra computer system. These changes should allow us to use atomic models with tens of thousands of configurations and produce more accurate simulations.

We simulate a generic laser heated tin plasma using HYDRA [2]. A design study shows how to select a target size and laser intensity that produce high conversion efficiency into the 13.5 nm bandpass. We will demonstrate the impact of a more detailed atomic database on this "optimized design".

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Presenting Author

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

P13

Characterizations of a Nd:YAG Laser-driven Plasma

O. O. Versolato, Dmitry Kurilovich

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1098 XG Amsterdam, The Netherlands

We present our findings relevant for the interaction of nanosecond-pulsed Nd:YAG laser light with tin micro-droplets that serve as mass-limited targets in plasma sources of extreme ultraviolet light. To obtain a better understanding of the myriad processes within the laser-generated plasma we recently performed charge-state-resolved measurements of the relevant tin ions using an electron beam ion trap as well as spectroscopic investigations of actual laser-produced plasma at ARCNL, enabling fingerprinting the individual contributions of the various charge states of tin to the spectrum of in-band, and out-of-band radiation. Further, we studied the tin ion energy distributions of both nanosecond- and picosecond-laser produced plasmas on solid as well as on droplet targets and compared our experimental findings to two self-similar solutions assuming isothermal expansion of the plasma plume into the vacuum.

Presenting Author

Dmitry Kurilovich is a PhD researcher in the EUV Plasma Processes group at the Advanced Research Center for Nanolithography (ARCNL) in Amsterdam, The Netherlands. Before starting his PhD research, he obtained a master's degree in Plasma Engineering and worked for two years as a researcher in the Research Center for Plasma Science and Technology, a collaboration between Max Planck Institute for Extraterrestrial Physics, Germany, and Bauman Moscow State Technical University, Russia, on the topic of low-temperature plasmas. His current research activities at ARCNL are focused on the physics of laser-droplet interactions and plasma diagnostics in tin-plasma-based sources of EUV light.

P14

EUV Source Optics with 100% OOB Exclusion

Kenneth C. Johnson

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Out-of-band (OOB) radiation is a problem for EUV lithography, which could become more acute with shrinking process windows and higher power levels that will be needed to overcome stochastic variability at future process nodes. Laser-produced plasma (LPP) EUV sources typically eliminate infrared laser radiation by using a diffraction grating on the collection mirror to diffractively scatter infrared radiation out of the intermediate-focus (IF) aperture. However, the undiffracted radiation includes EUV plus a significant amount of DUV radiation, which impacts the lithography process.

A different type of diffraction grating could achieve 100% full-spectrum OOB rejection by operating the LPP source as an EUV monochromator, which efficiently transmits diffracted EUV radiation (not undiffracted radiation) through the IF aperture. Other diffracted wavelengths are fully excluded from the aperture via chromatic dispersion. This OOB solution could be straightforward to implement, requiring only replacement of the collection mirror during routine maintenance. This poster presentation will illustrate the optical design concept of the monochromator grating. Two possible grating structures – "conformal multilayer" and "patterned multilayer" – will be described and compared to existing IR-diffracting collectors. Their optical performance, in terms of EUV collection efficiency and OOB rejection, will be quantified based on simulations with rigorous coupled-wave analysis.

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Presenting Author

Ken Johnson is a specialist in optical systems modeling and design, with an emphasis on diffraction optics. His "Grating Diffraction Calculator" (GD-Calc) software is widely used in industry, academia, and defense research for diffraction grating simulation, and he is currently developing a successor to GD-Calc based on recently-developed generalizations of coupled-wave theory. His published research includes potential applications of diffraction optics for semiconductor manufacture, such as maskless lithography and actinic EUV mask inspection and metrology.

P15

Compact Efficient CO_2 Amplifiers with Modular Design for Highly-efficient EUV Power Generations

Koji Yasui[1] and Naoya Kishida[1]
Tatsuya Yamamoto[2] and Jun-ichi Nishimae[2]
Masashi Naruse[3], Sugihara Kazuo[3], and Masato Matsubara[3]

[1]Mitsubishi Electric Corporation, Head quarter, Factory Automation Systems Group, Tokyo, Japan
[2]Mitsubishi Electric Corporation, Advanced technology R&D center, Hyogo, Japan
[3]Mitsubishi Electric Corporation, Nagoya works, Nagoya, Japan

CO_2 amplifiers have been developed and the performances are confirmed for EUV generation systems so that they could be adapted for commercial applications. Based on transverse-gas flow design, electrically efficient operation and compact foot space compared with conventional lasers are achieved. At the workshop, we are also going to discuss the modular design for the variety of process conditions. Our basic system generates CO_2 powers of 5-10kW and simply by adding same three amplifiers, the CO_2 powers can be increased at least 10kW per each amplifier so that total powers of more than 35-40kW could be generated. Therefore, today's 250W EUV applications could be generated adapting three amplifiers. However, if the EUV power of 100W is enough for some lithography conditions, it should be selectable by applying one amplifier and the EUV power can be enhanced easily by adding more amplifiers in the near future if higher EUV power is required.

Presenting Author

Koji Yasui received B.S. and Ph. D. degrees from the University of Tokyo in 1982 and 1989 respectively. He was a visiting scientist at the Stanford University in 1989. He joined Mitsubishi Electric Corporation in 1982, where he has developed high-power CO_2 lasers, high-power solid-state lasers, high-power green lasers, high-power 266nm UV lasers and laser processing machines using those laser sources. He is now working as a senior chief engineer and as a senior chief technologist in charge of laser technology, EDM technology, CNC technology and e-beam technology and related businesses.

P16

Xenon Plus Additives in the Energetiq EQ-10

Stephen F. Horne, Don Smith, Matt Partlow, Debbie Gustafson, Paul Blackborow

Energetiq Technology, Inc.

A search of the older EUV literature reveals various attempts to improve the performance of Xenon discharge EUV sources by the addition of other gasses [1,2,3,4]. Significant (upto 40%) increased EUV power has been reported using helium dilution to give ~ 15% xenon partial pressure, compared to operation in pure Xenon. Early in the development of the EQ-10 Electrodeless Z-pinch source, we experimented briefly with helium injection. Recently we have revived the idea, to address an un-related problem. When the EQ-10 is used in an application requiring a relatively large source etendue, the nature of the electrode-less discharge causes a plasma plume to exit the source. This plume can carry substantial energy. To dissipate this energy, we rely on nitrogen injection in the beamline. The fact that nitrogen is molecular (hence radiates efficiently in the IR) and is electronegative, removes both energy and electrons from this plume and efficiently shields downstream structures. However nitrogen diffusing upstream into the source discharge can cause the source plasma to become less stable.

The high ionization energy of helium, and the low mass of the helium ion (both compared to xenon) imply that when mixed with the source xenon it should not participate (to zero order) in the z-pinch electrodynamics. Therefore by injecting helium into the source, the total flow rate might be increased (compared to pure xenon operation) to assist in flushing nitrogen from the source. In addition to this idea, we plan to investigate whether a dual-gas injection system will increase the EQ-10 source brightness and/or power. This idea relies on injecting Xenon directly into the bore, while supporting the plasma return loops (which in the EQ-10 play the role of the electrodes) with an argon plasma. We are planning a series of experiments to explore these concepts. We will present those plans, and our earlier data on Xe/He mixed gas in the EQ-10.

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Presenting Author

P17

High-brightness Tabletop Coherent EUV Source for Metrology with Sub-10-nm Resolution

G. Fan[1], T. Balčiūnas[1,5] ,E Kaksis[1,2], X. Xie[1], A Pugžlys[1], P Carpeggiani[1], K. Légaré[2],
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[5]GAP-Biophotonics, Université de Genève, Geneva, Switzerland
[6]Université Pierre et Marie Curie, Paris, France

We present a high brightness coherent soft x-ray source based on HHG driven by sub-terawatt (ytterbium) Yb laser system reaching 5.6nm wavelength. So far, Ti:Sapphire laser at 800nm are the most popular source for HHG, either directly or by pumping OPA. Yb lasers are more compact and able to scale to higher power at the price of longer pulse duration. After hollow core fiber compression, we achieved 20fs, 10mJ pulses centered at 1um with 2kHZ repetition rate. In HHG, the cut-off photon energy scales as λ2 , thus it can be extended by 55% as compared to Ti:Sapphire. Via HHG in Helium, we obtained femtosecond, spatially coherent and bright (>1027photons/s mrad2 mm2) soft Xrays with cut-off at 5.6nm. As compared to mid-IR driven HHG sources, we achieved orders of magnitude higher brightness with a simpler and more compact system. We use this soft x-ray source for diffraction of magnetic nanostructures with high temporal and spatial resolution. To date, similar measurements have only been accomplished in large-scale X-ray facilities. The flux (~uW) requirements of such experiment is compatible with condition for advantaged EUV metrology for nanoelectrics, mask defect inspection and in support of EUV lithography of sub-10 nm technology scaling. The output energy of our laser is being improved and higher pulse compression ratio has been recently demonstrated by other groups. This offers prospective of increased flux and extending the limit to short wavelength.

Presenting Author

P18

Storage Ring EUV Light Source Based on Steady State Microbunching Mechanism

Xiujie Deng

Tsinghua University, Beijing, China
On behalf of the SSMB Collaboration

An initial task force has been established in Tsinghua University to design an electron storage ring aiming at generation of kW level EUV radiation based on the steady state microbunching (SSMB) mechanism. In this paper, the basic idea of SSMB as well as the potential advantages of applying it for EUV lithography are briefly reviewed. The main tasks of the collaboration at this moment, which consist of the dedicated EUV SSMB lattice design, the effort to address related technical challenges and the preparation of proof-of-principle experiment, are then presented.

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) in an electron storage ring.

P19

Accelerator based Extreme- Ultraviolet (EUV) Sources for Lithography

J. Wu and A.W. Chao

SLAC

Extreme ultraviolet lithography (EUVL) is a next-generation lithography technology using an extreme ultraviolet (EUV) light source, currently at 13.5 nm. We will first review a few accelerator based approaches for EUV source generation, including Laser Induced Microbunching (LIM) schemes, High-Gain Inverse Compton (HGIC) source, etc. Besides the high average power required by EUVL; for industrial applications, EUV source's reliability, stability, reproducibility, and repeatability are all important measures. A storage-ring based steady state microbunching (SSMB) configuration (Chao, Int. J. Mod. Phys. A, 2015) is a very promising approach providing EUV source at kilowatts level average power meeting the high throughput requirement for EUVL. Detailed system optimization, in particular for a reversible SSMB configuration, is carried out considering various accelerator physics in the storage ring and laser physics effects in the modulators and the radiator. The SSMB system size is also carefully designed aiming to be compatible with the lithography tools. Such accelerator baser EUV sources are compared to others approaches, such as laser-produced plasma (LPP) source.

Presenting Author

Juhao Wu received his Ph.D. in physics from State University of New York at Stony Brook (Stony Brook University) in 2002. He has since then been working at SLAC National Accelerator Laboratory. He works in the area of accelerator and beam physics in general with an emphasis on X-ray free electron lasers (FEL). He was one of the commission team core members of the world's first Hard X-ray FEL and received the DOE Secretary of Energy Appreciation Award in 2010. He has been actively conducting accelerator and beam physics R&D and received the DOE Early Career Research Program Award in 2013.

P21

A Sustainable Approach to Next Generation EUV Manufacturing

S.L. Jaiswal

Astrileux Corporation

A sustainable approach to next generation EUV manufacturing is considered from the perspective of EUV optics and EUV mask. The selection of EUV lithography at wavelength of 13.5 nm is primarily based on the reflectivity of EUV multilayer Bragg mirrors and is at the heart all decisions made in next generation EUV lithography design, manufacturing, and sustainability. Traditional EUV optics are based on Mo-Si multilayers reflecting at 13.5 nm, ruthenium capping layers, and boron carbide interfacial barrier layers. However their performance using light sources at 250 W and higher is relatively untested. For sustainable EUV manufacturing we need to evaluate both lifetime performance of EUV optical coatings at high power and the overall energy consumption lithography tools, and understand the role played by these seemingly passive components in the overall energy budget. We consider both current and alternative approaches to EUV manufacturability with a view to understanding the requirements of sustainability for future generations.

Presenting Author

Supriya Jaiswal is the CEO and of Astrileux Corporation, a next generation semiconductor company. Supriya holds a Bachelors and Masters degree in Physics, from University of Oxford, UK, Masters degree in Atomic Physics and a PhD in Engineering Physics from University of Virginia, and professional accreditation in Business and Finance from University of California, San Diego. In 2015 Supriya was elected to SPIE Senior Member for distinction and significant contributions in optics and photonics. She was the finalist judge on the 2015 SPIE Photonics West Start-Up Challenge. She was listed on SPIE's 2016 Women in Optics. Astrileux is the winner of the 2018 EIPBN best start-up award, the 2016 Material Research Society innovations in material science competition, and the 2015 winner of the Semicon West innovations showcase. Astrileux is funded by National Science Foundation, DOE and CASIS, the Center of Advancement of Science in Space, managed by the International Space Station. In 2015 Astrileux was voted at one of San Diego's coolest start-ups by the venture capital community.

P22

Optics for EUV Lithography

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 allows 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 EUV Lithography are being produced in significant numbers as commercial optical components for EUVL scanners.

The next step of EUV Lithography is already in the making: High-NA EUV is envisioned to be the summit of lithography with ultimate resolution – supporting the continuation of the shrink roadmap.

The status and technical challenges of optics for EUV Lithography in general and of the high-NA EUV optics development in particular 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.

P23

Corrosion-resistant Mg-based multilayer coatings for sources > 25 nm

Regina Soufli

Lawrence Livermore National Laboratory, Livermore, California, US

The 25-80 nm wavelength region is part of the operational range of extreme ultraviolet (EUV) synchrotron, free-electron laser and tabletop laser sources, which often require multilayer-coated reflective optics. Mg/SiC possesses a unique combination of favorable reflective properties in the 25-80 nm wavelength range: high reflectance, near-zero film stress, good spectral selectivity and thermal stability up to 350☐ C. However, Mg/SiC suffers from Mg-related atmospheric corrosion, an insidious and unpredictable problem which completely degrades reflectance and has prevented Mg/SiC from being used in scientific experiments and applications that require long lifetime stability. In recent work, we elucidated the origins and mechanisms of corrosion propagation within Mg/SiC multilayers and demonstrated efficient Al-Mg corrosion barriers for Mg/SiC multilayers. In this presentation, we discuss the physics of spontaneous intermixing and amorphization of the Al and Mg layers inside the Al-Mg corrosion barriers and the long-term reflective properties of a variety of Mg/SiC multilayer concepts, with and without corrosion barriers.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

Presenting Author

P24

Ar Plasma Discharge Sources for EUV/SXR Metrology and Imaging

Ladislav Pina

Czech Technical University in Prague (Czech Republic)

Metrology and imaging in EUV and SXR spectral regions are of increasing interest. Material science, biology and hot plasmas are examples of fast developing areas. Applications include spectroscopy, astrophysics, EUV lithography, Water Window microscopy and micro-tomography. Improvements of metrology capabilities in terms of resolution, recognition and speed are still challenging. Selected results of Ar plasma discharge source studies are presented together with relevant optical systems.

Presenting Author

P25

Ion Fluxes Impacting Surfaces Exposed to EUV Induced Plasma

T.H.M. van de Ven[1], C.A. de Meijere[2], R.M. van der Horst[2], V.Y. Banine[1,2]
and J. Beckers[1]

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[2] ASML, De Run 6501, 5504 DR Veldhoven, The Netherlands

In technical applications involving EUV radiation, a fraction of the high energy photons is absorbed by low pressure background gas, creating a plasma everywhere the EUV travels. EUV optics and other delicate components exposed to this EUV induced plasma endure fluxes of ions that are accelerated towards the surface by plasma induced electric fields. It has been proposed that these ions can affect EUV optics surface conditions both positively and negatively, by for example cleaning of carbon contamination [1] and delamination in multilayer mirrors [2]. Key elements are the ion flux density and the ion impact energy distributions.

We have investigated the ion fluxes under EUVL scanner relevant conditions. An RFEA and ion mass spectrometer have been used to measure ion flux densities and energy distribution functions in pulsed EUV-induced plasmas in hydrogen gas. The magnitude and temporal evolution of the ion flux densities can be described classically using photoionization and ambipolar flow. The evolution of the ion energy distributions does not agree with the electron temperatures associated with the flux densities, which indicates the presence of energetic electrons. Understanding this behavior is essential to predict the impact on EUV optics and other exposed components.

[1] A. Dolgov et al, J. Phys. D. Appl. Phys., 47, 065205, 2014.
[2] A. Kuznetsov et al, Proc. SPIE, 8077, 2011.

Presenting Author

Tijn van de Ven is a Ph.D. candidate at the Eindhoven University of Technology, the Netherlands. During his MSc. in Applied Physics he specialized in plasma and radiation physics. He is currently pursuing his Ph.D. under supervision of Vadim Banine and Gerrit Kroesen. His research is on ion fluxes towards surfaces exposed to plasma induced by EUV radiation.

P31

Coherent EUV Imaging and Metrology with High-harmonic Generation Sources

Stefan Witte

ARCNL and VU University Amsterdam

Coherent light sources are powerful tools for metrology, as they enable measurements that are sensitive to the phase of a light field rather than just the intensity. Phase-sensitive detection provides access to a sub-wavelength scale in both space (sub-nanometer) and time (attoseconds). High-harmonic generation (HHG) is a process that enables the production of fully coherent pulses of extreme-ultraviolet (EUV) and soft-X-ray radiation using compact high-intensity lasers. The short-wavelengths and associated high photon energies of EUV radiation give rise to very different light-matter interaction compared to visible light: EUV radiation can diffract from nanostructures, penetrate optically opaque materials, and probe inner-shell electrons in atoms and molecules. However, broadband EUV measurement methods are highly complex due to extreme stability requirements and the challenges of optical components. I will explain our approach to EUV interferometry and metrology and discuss various applications such as high-resolution spectroscopic lensless imaging through computational image reconstruction from coherent diffraction patterns.

Presenting Author

Stefan Witte received his PhD in 2007 from the Vrije Universiteit Amsterdam, for work on intense ultrafast laser development and precision spectroscopy. He did postdoctoral work at on nonlinear microscopy and biomedical imaging (Vrije Universiteit) and on ultrafast electron dynamics and lensless imaging with high-harmonic sources (JILA, University of Colorado).

Since 2014 he is a group leader in the EUV Generation and Imaging group at the Advanced Research Center for Nanolithography (ARCNL) and assistant professor at the Vrije Universiteit Amsterdam. His present research interests include coherent diffractive imaging and metrology with visible and EUV radiation, high-harmonic generation and its applications, and advanced laser development for plasma experiments.

P32

Full Field Imaging at 13.5nm in Reflection and Transmission Modes using Coherent High Harmonic Beams for EUVL and Materials Metrology

Henry Kapteyn[1,2], Margaret Murnane[1,2] and Kevin Fahey[2]

[1]*JILA, University of Colorado at Boulder and* [2]*KMLabs Inc.*

With increasing device density and the advent of EUVL, 3D devices are increasingly becoming the norm. This creates a growing need in the semiconductor industry and in materials science for high spatial resolution, non-destructive metrology techniques. The relatively new capability to generate coherent EUV light on a tabletop scale using the high-order harmonic generation process presents many new possibilities for semiconductor metrology. In this talk, we present our work to realize two such capabilities, both of which make use of ptychographic coherent diffractive imaging (CDI) implemented using our commercially available tabletop 13 nm source, the XUUS™. The first is an actinic mask inspection microscope that can provide direct amplitude and phase images of a mask at resolution suitable for both current and future generations of EUVL, in a format ideal for prediction of print illumination. The second is an imaging reflectometer capable of determining depth-dependent composition information on devices. This complex EUV imaging reflectometer is capable of imaging at a range of angles from near-normal incidence to near-glancing incidence, for high resolution imaging and for determining spatially-resolved composition vs. depth profiles of samples. By harnessing phase measurements, we can also locally and non-destructively determine quantities such as device and thin film layer and oxide thicknesses, surface roughness, interface quality, and dopant concentration profiles. Using this advanced imaging reflectometer, we can quantitatively characterize materials-science-relevant and industry-relevant nanostructures for a wide variety of applications, spanning from mask metrology, to defect and overlay metrology to the development and optimization of nano-enhanced thermoelectric or spintronic devices.

1. "General-purpose, wide field-of-view reflection imaging with a tabletop 13nm light source", Optica 4(12) 1552-1557 (2017).
2. "Sub-wavelength coherent imaging of periodic samples using a 13.5 nm tabletop high harmonic light source," Nature Photonics 11, 259 (2017).
3. "Imaging Buried Nanostructures using Extreme Ultraviolet Ptychographic Coherent Diffractive Imaging," Nano Letters 16 (9), pp 5444–5450 (2016).
4. "High contrast 3D imaging of surfaces near the wavelength limit using tabletop EUV ptychography", Ultramicroscopy 158, 98–104 (2015).
5. "Beyond Crystallography: Diffractive Imaging with Coherent X-ray Sources", *Science* 348, 530 (2015).

Presenting Author

Dr. Kevin P. Fahey PhD was appointed CEO of KMLabs Inc. in April 2018. He has previously served as the Chief Executive Officer of Xradia, Inc. and of Metrosol, Inc. and has been the Senior Vice President of Marketing and Products for Carl Zeiss Microscopy, the Digital Marketing Officer for Carl Zeiss Corporation, and the Vice President and General Manager of the Fab Market Division of FEI Company. He has over 20 years of proven management experience in the high tech sector with successful leadership roles in R&D, sales & marketing, international business, and high volume production. Dr. Fahey holds a Ph.D. and an M.S. in Materials Science and Engineering from Stanford University and a B.S. in Physics from the Massachusetts Institute of Technology.

P33

Evaluating Thermal and Mechanical Properties of Composite Films for EUV Pellicle Applications

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

[1] Division of Materials Science and Engineering
[2] Division of Nanoscale Semiconductor Engineering
Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Korea

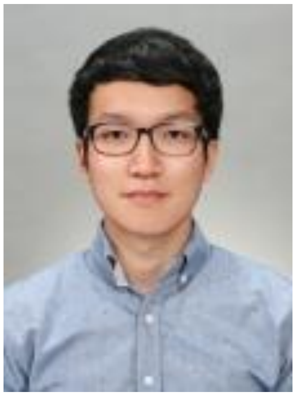
Mechanical durability of EUV pellicle is necessary to tolerate mechanical load by the stage motion and pressure change in the chamber. Thermal stability is also required to withstand the thermal load by EUV exposure. Composite films with reinforcing layers and/or thermal emission layers can provide mechanical/thermal stability of EUV pellicle. In this paper, the composite films were fabricated and evaluated.

In order to fabricate composite films, SiN_x was deposited on silicon wafer. Then, the carbon-based material was transferred or deposited on top of that, and the membrane was fabricated using a KOH solution. Ru and B_4C film was deposited to improve thermal emission property. The mechanical properties such as Young's modulus and residual stress of pellicles were derived through bulge test and nano-indentation. The temperature of pellicle surface was measured by optical pyrometer under UV irradiation emulating EUV exposure conditions.

The strengthening effect of carbon-based materials were verified by comparing the mechanical properties of silicon-based single layer and composite films. Various emission layers were compared and the results show the emission efficiency depends on the stacking sequence of the composite films. Through adopting reinforcing layers and thermal emission layers, the mechanical and thermal properties of pellicle membrane can be improved.

Presenting Author

SeongJu Wi is a graduate student under Prof. Jinho Ahn in the Nano Process & Device Laboratory, Department of Materials Science & Engineering, Hanyang University, Seoul, KOREA.



P35

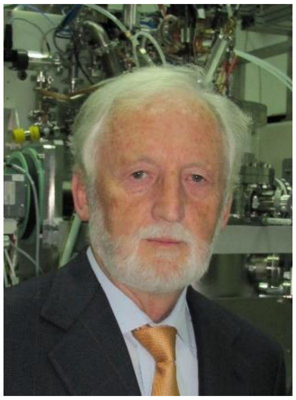
Electron Multi-Beam Technology enabling EUV Mask Writing

Hans Loeschner and Elmar Platzgummer

IMS Nanofabrication GmbH, Schreygasse 3, 1020 Vienna, Austria

In his plenary talk at SPIE Advanced Lithography in February 2018 Stephen Hsu / ASML Brion pointed out: "*The introduction of the multi-beam mask writers enables ILT to become a practical solution*". IMS Nanofabrication's MBMW-101 mask writer tools have meanwhile been in use by several industry customers for more than one year. This presentation will give an overview of recorded tool performance data and availability. In fact, multi-beam writing has proven to meet industry expectations in terms of enabling a higher exposure dose without productivity tradeoff, and accelerating cycle time despite largely enhanced pattern complexity. Hence, MBMW-101 has already become the preferred solution, if not the only practical, for EUV mask writing and/or 193i ILT. Both CDU and Registration do not only meet the targeted 7nm mask node requirements, as with recent tool improvements also 5nm lithography requirements can be met. The reliability in operation has been demonstrated, especially the multi-beam generator (aperture plate system) and the data path has shown a high degree of stability: Virtually no lifetime limiting factor for the key components has been found. Specific benefits of using curvilinear "ideal" ILT for EUV masks will be discussed.

Presenting Author



Hans Loeschner is co-founder and senior advisor of IMS. During his PhD effort in semiconductor physics he worked at the Philips Research Laboratories in Eindhoven, The Netherlands. After finalizing his studies at the University of Vienna, for several years he focused on ion beam resistless patterning at a former Vienna based company. In 1985 he became co-founder of IMS - Ion Microfabrication Systems and in 2006 of IMS Nanofabrication. In 2012 he received the MNE Fellowship Award "*for his outstanding contributions to the advancement of electron and ion beam technologies*", and in September 2017 together with CEO Elmar Platzgummer the SPIE 2017 BACUS Prize "*in recognition of their contribution to the photomask industry through their work and influence to develop and commercialize high keV Multi-Beam photomask lithography tools*".

P36

Application of EUV Diffraction Optics for Actinic Mask Inspection and Metrology

Kenneth C. Johnson

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

Diffractive EUV microlenses comprising patterned molybdenum structures on a silicon membrane can theoretically exhibit EUV transmittance in excess of 60% in the first diffraction order. Such lenses can be combined in pairs ("Schupmann doublets") to generate achromatic point sources for a spot-scanning EUV microscope. In an actinic mask inspection/metrology system, a Schupmann microlens array would partition radiation from a laser-produced plasma source into multiple, point-divergent beams, which are imaged to diffraction-limited focal points on a reflective mask surface. The reflected beams are imaged onto a multi-megapixel detector array, which acquires signal data as the mask is raster-scanned across the focal point array. The microlens geometry is designed to neutralize aberrations in the EUV projection optics, providing aberration-free point imaging over the entire array.

This paper details the design and performance of diffractive EUV Schupmann doublets, including structure geometry, optical efficiency, achromatization, and aberration compensation. An illustrative actinic mask inspection system is outlined and estimated performance characteristics are derived including image resolution, detector signal level, and throughput. A Fourier optics simulation illustrates the system's sensitivity to mask phase defects.

References

For EUV Schupmann microlenses:
K. Johnson, "Scanned-spot-array extreme ultraviolet imaging for high-volume maskless lithography", Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena 30, 051606 (2012); https://doi.org/10.1116/1.4752112

For actinic mask inspection/metrology:
K. C. Johnson, US Patent App. 15/269,848, 2017

Presenting Author

Ken Johnson is a specialist in optical systems modeling and design, with an emphasis on diffraction optics. His "Grating Diffraction Calculator" (GD-Calc) software is widely used in industry, academia, and defense research for diffraction grating simulation, and he is currently developing a successor to GD-Calc based on recently-developed generalizations of coupled-wave theory. His published research includes potential applications of diffraction optics for semiconductor manufacture, such as maskless lithography and actinic EUV mask inspection and metrology.

P37

Advances in High-volume Manufacturing of EUV Mask Blanks: Current Status and Roadmap

Meng Lee, Sandeep Kohli, Katrina Rook, Boris Druz, Frank Cerio,
Adrian Devasahayam

Veeco Instruments Inc (United States)

Over the next decade extreme ultra-violet (EUV) lithography will play critical role in 7 nm and lower process nodes. Multilayered molybdenum (Mo)/ silicon (Si) mask blanks are a key component of high-volume manufacturing (HVM) using EUV. The deposition processes and methods for Mo/Si have evolved significantly over time keeping in pace with the requirements of EUV market. While the technical risks of defects for the mask blank are much lower at this time, more advances are needed to improve yield from these masks, have better process control and further improve defects as applications of EUV lithography are further challenged (example multiple patterning). Further technical improvements are needed to follow the existing HVM ramp while keeping improvements from the past.

In this presentation, we will explore some of the recent improvements for the mask blank manufacturing using Veeco NEXUS IBD-LDD Ion Beam Deposition System. For example recent technical and handling improvements have led to production of significant number of 0-defect masks at > 54 nm [1] and a beam over spray reduction of > 50 x [2]. We will also present technical roadmap for improvements in the mask manufacturing to further improve defect levels, yields and throughput to enable HVM ramp. Some new ideas and platforms will be introduced for this.

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)

Presenting Author

P38

EUVL Mask Engineering in the Third Dimension: The Impact of Absorber Side-wall Angles on Imaging Behavior

Tim Fühner [a], Lawrence S. Melvin III [a], Yudhishthir Kandel [a], Weimin Gao [b]

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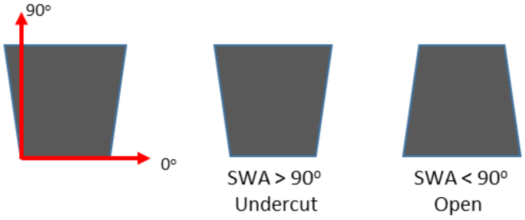
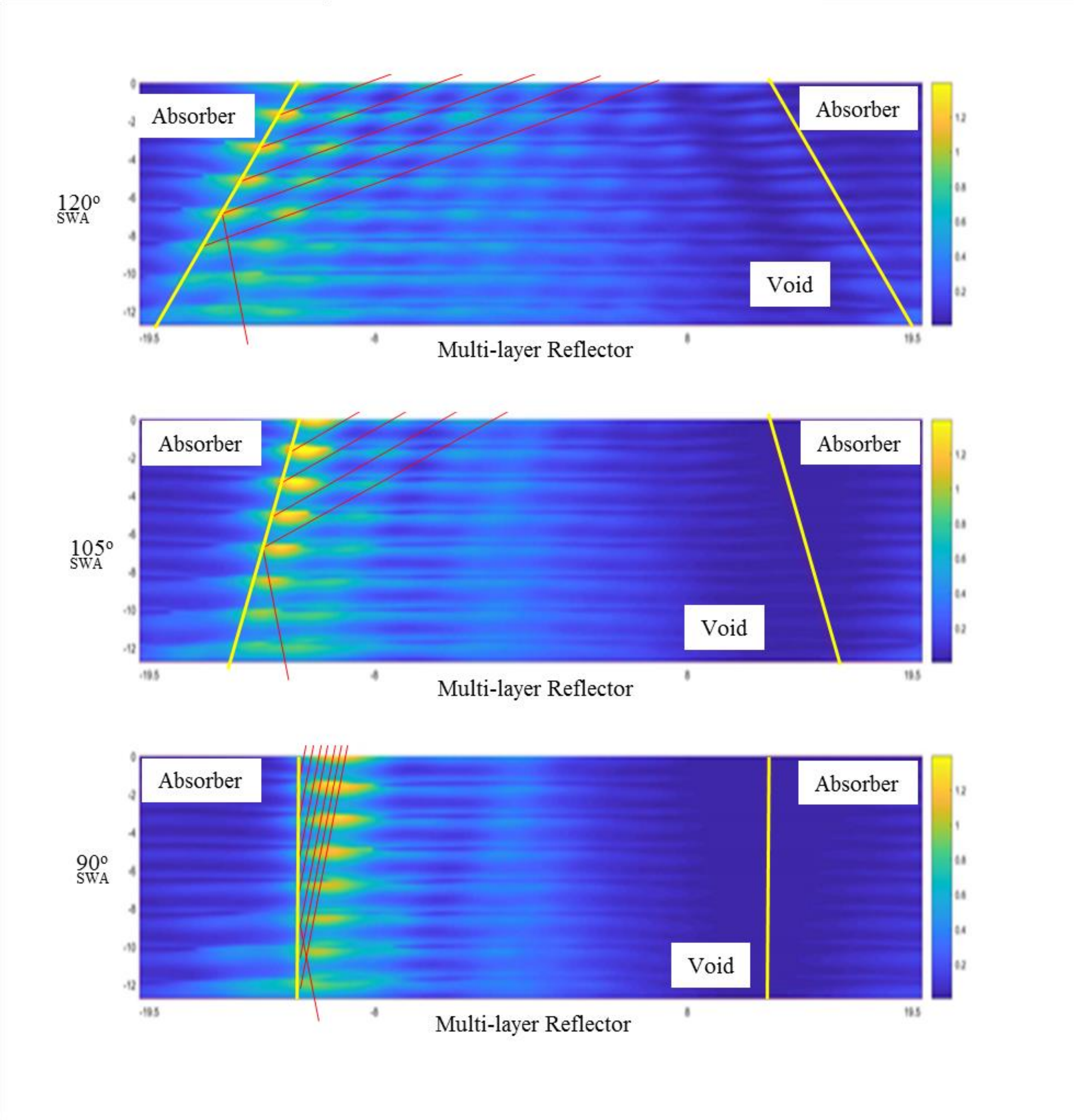
[b] *Synopsys Inc., Technologielaan 11-0002B-3001 Leuven, Belgium*

The non-normal chief ray angle causes EUVL to suffer from severe imaging complications such as pattern shifts, shadowing and aggravated mask 3-D effects. Moreover, scattering differs depending on how an edge is oriented and whether it is facing the bright or the dark side of the illumination source, leading to an asymmetric image contrast. Numerous techniques have been proposed to mitigate these effects, including asymmetric mask features and sources, and modifications of the absorber material. In this work, a 3-dimensional absorber engineering approach is proposed: Using oblique side-wall angles, simulations show a significantly improved light distribution in the space between features. This translates into steeper and more symmetric slopes in the aerial image. Counter-intuitively, undercut side-wall angles show a substantially larger contrast compared with acute or open angles. Comprehensive diffraction and process window analyses that clarify the cause of this behavior have been conducted and are discussed. To assess the manufacturing feasibility of this approach, a dedicated study on the sensitivity of slight variations from an ideal side-wall angle has been performed. Finally, side-wall angle modification interactions with different absorber materials including those with high extinction coefficients were investigated.




120°
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105°
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0
-2
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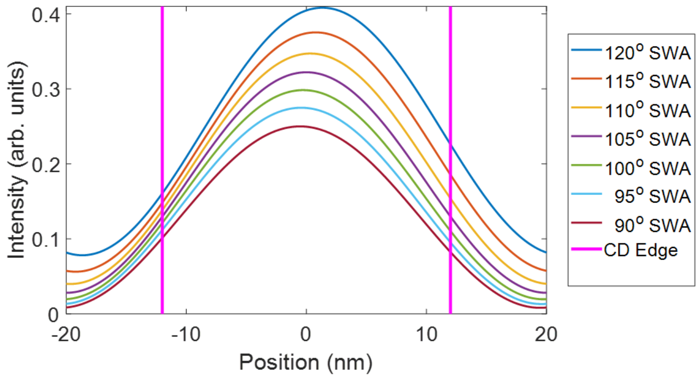

Intensity (arb. units)
0.4
0.3
0.2
0.1
0
-20
-10
0
10
20
Position (nm)
120° SWA
115° SWA
110° SWA
105° SWA
100° SWA
95° SWA
90° SWA
CD Edge

Presenting Author

Tim Fühner joined the Silicon Engineering Group of Synopsys in 2017, where he helps develop advanced mask and imaging models for mask synthesis. For more than 15 years, he has been working at the Fraunhofer IISB in Germany, where he has investigated the adoption of heuristic optimization approaches to a number of different applications including crystal growth and lithographic processes. In addition to his research activities in optimization and computational lithography, he has led the development of the Fraunhofer IISB simulator Dr.LiTHO. Tim earned a master's degree in computer science at the University of Erlangen-Nuremberg, Germany, from where he was also awarded a Ph.D., also in computer science.

P39

Fourier Space Spectral Analysis in EUV Reticle Imaging Using RESCAN: Facets & Advantages Offered by a Lensless Tool for Actinic Mask Inspection

Rajeev Rajendran, Sara Fernandez, Patrick Helfenstein, Iacopo Mochi and
Yasin Ekinci

Paul Scherrer Institut, 5232 Villigen, Switzerland

RESCAN is an actinic pattern inspection (API platform based on scanning coherent diffraction imaging (SCDI), under development at the Paul Scherrer Institut. This research tool uses coherent illumination to record diffraction images and computationally recover high-resolution actinic maps of the EM wave, exiting the reticle, without using imaging optics. The lensless imaging technique employed in RESCAN allows the potential of direct Fourier space computational operations for the various imaging modalities (bright field or dark field), image quality enhancements and plausible mask 3D-effects quantification within the same tool. This along with the ability to simultaneously retrieve both the reticle amplitude and phase maps, makes RESCAN one of the most promising solutions for API. In this paper, we discuss the fundamentals of SCDI and its advantages and challenges. We demonstrate its potential for API with our recent experimental results including defect analysis on logic patterns, through-pellicle inspection, absorber material analysis, and blank inspection. Furthermore, a roadmap for extending the capabilities of RESCAN to high-NA imaging and increased throughput will be discussed.

Presenting Author

Rajeev Rajendran is an optical and imaging physicist and presently a Research Scientist at Paul Scherrer Institut in Switzerland, where he is involved in the development of a lenless actinic metrology tool for mask inspection. Prior to this he was a post-doctoral fellow at ETH-Zurich and was instrumental in developing self-monochromatised coherent sources using high harmonic generation. He was also a visiting fellow at University of Maryland, College Park where he worked on the prospects of Direct Laser Acceleration of electrons using corrugated plasma waveguides. In his PhD he had as a first devised the concept of laser-driven table-top accelerator for energetic neutral atoms with applications in neutral beam lithography. For this work he had received the Saraswathi Cowsik Medal in 2013.

P41

Percolation Model of the Stochastic Effect of EUV Resists

Akira Sasaki, Masahiko Ishino, Masaharu Nishikino, and Yasunari Maekawa

Group of EUV ultra-precision technology, QST Advanced Study Laboratory

We present a numerical model based on the percolation [1] of photoresists. Using the EUV light, radiation chemistry due to low-energy secondary electrons, which are produced after the absorption of EUV photons, have an important role in the image formation. We model a resist molecule, which consists of metal clusters, as a cube with the side of 1 nm, which connects to adjacent molecules by the irradiation of an EUV photon to produce the negative-tone image. We investigate the average line width and roughness as a function of dose to see find the threshold dose for image formation. We also investigate the effect of the shot noise due to the absorption of small number of EUV photons.

Reference:

[1] W. Hinsberg, Proc. SPIE 10146 (2017) 1014604.

Presenting Author

Akira Sasaki received the Dr. Eng. degree in energy science from Tokyo Institute of Technology, Tokyo, Japan in 1991. He joined Japan Atomic Energy Agency in 1996; the organization has changed in 2016 to Kansai Photon Science Institute, National Institutes for Quantum and Radiological Science and Technology. He has been studying theoretical modeling and simulation of the atomic processes and radiation hydrodynamics of EUV source for lithographic applications since 2002.

P42

Pushing the Resolution Limits of Photolithography

Yasin Ekinci

Advanced Lithography and Metrology Group, Paul Scherrer Institute
5232 Villigen PSI, Switzerland

Extreme ultraviolet (EUV) lithography is currently considered as the most promising alternative to DUV immersion lithography for high-volume semiconductor manufacturing at 7 nm technology node and below. In addition to its short-wavelength, one of the main advantages of EUV light is its relatively small secondary-electron blur, which is an important but relatively unexplored aspect of EUVL. In this presentation, I discuss our recent attempts to quantify this effect. At PSI we are operating an EUV interference lithography (EUV-IL) platform which has been a powerful tool for academic and for industrial research. EUV-IL combines the simplicity of IL and the short wavelength advantage of EUV light, and therefore is an effective method of making high-resolution nanostructures. The EUV-IL platform at PSI is the world-leading tool with a resolution of down to 6 nm half-pitch, marking the world record in photolithography. With chemically-amplified EUV resist, we could reach down to 11 nm hp. Since EUV-IL provides high-resolution aerial images, has low cost, and it is relatively simple and flexible, it enables academic researchers and companies to develop materials, in particular in early development stages. In this presentation, I discuss the advantages and challenges of EUV-IL and show recent results of our evaluation of EUV resists.

Presenting Author

Dr. Yasin Ekinci is a Group Leader for Advanced Lithography and Metrology at Paul Scherrer Institut in Switzerland.

P43

Stochastic Methods for Informing EUV Lithography

Aamod Shanker[1], Antoine Wojdyla[2], Gautam Gunjala[1], Markus Benk[2], Andy Neureuther[1], Patrick naulleau[2], Laura Waller[1]

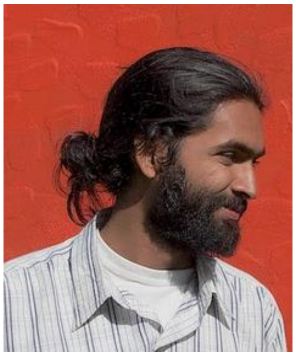
[1]Dept of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA

[2]Center for X-Ray Optics, Lawrence Berkeley National Lab, Berkeley, CA

EUV lithography at the cusp of maturity is confronted with enhanced stochastic effects in lithography optics and resist materials in the sub 20nm X-ray regime, where roughness is comparable to critical dimensions. We demonstrate practical methods for utilizing stochastic effects for optical/material metrology and design. Experiments at ALS beamlines demonstrate aberration recovery of EUV optics from beam speckle, and post-develop line edge roughness characterization from the bulk stochastic properties of EUV photoresist.

Presenting Author

Aamod is an affiliate student at the Lawrence Berkeley National Laboratory, where he is researching phase imaging methods with applications in microscopy and lithography. His undergraduate degree was from the Indian Institute of Technology, Kharagpur, India in 2011.



P44

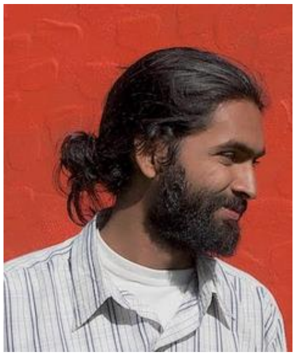
Inverse Problems in Turbulent Light

Aamod Shanker

Dept of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA

The differential equations underlying the non-linear dynamics of turbulent fluid flow are extended to the transport of optical energy and optical phase in coherent optics in a new theoretical framework. Since light acts like a pure, incompressible, inviscid fluid, the momentum and mass transport of the Navier-Stokes equations translate directly to the intensity and phase transport equations in scalar diffraction theory, respectively. The non-linear term in the phase transport equation describes the emergence of turbulent dynamics near cusps and singularities in the optical field, enabling insights into the topology and dynamics of turbulence/speckle in 6D phase space. A better understanding of the mathematical forms of turbulent wave dynamics allows for an improved understanding stochastic optical effects in sub 20 nm extreme ultraviolet lithography.

Presenting Author



Aamod is an affiliate student at the Lawrence Berkeley National Laboratory, where he is researching phase imaging methods with applications in microscopy and lithography. His undergraduate degree was from the Indian Institute of Technology, Kharagpur, India in 2011.

P46

Numeric Model for the Imaging Mechanism of Metal Oxide EUV Resists

W.D. Hinsberg[1] and S. Meyers[2]

[1]Columbia Hill Technical Consulting, Fremont CA
[2]Inpria Corporation, Corvallis OR

A numeric model is proposed describing the chemical and physical mechanisms governing image formation in metal-oxide (MOx) EUV photoresist systems. Experimental measurements of physical and chemical properties are used to develop a quantitative representation of the chemical and physical state of the MOx resist film at each step in the lithographic process. The role of radiation-induced condensation to drive non-linear changes in development rate is elucidated. Lithographic performance parameters are predicted and compared with experimental results.

Presenting Author

P47

Fundamental Understanding of Chemical Processes in EUV Lithography

Oleg Kostko,[1] Bo Xu,[1] Musahid Ahmed,[1] Daniel S. Slaughter,[1] D. Frank Ogletree,[2]
Kristina D. Closser,[2] David G. Prendergast,[2] Patrick Naulleau,[3] Deirdre L. Olynick,[2]
Paul D. Ashby,[2] Yi Liu,[2] William D. Hinsberg,[4] Gregory M. Wallraff[5]

[1]Chemical Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[2]Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, CA USA
[3]Center for X-Ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[4]Columbia Hill Technical Consulting, Fremont, CA USA
[5]IBM Research Center, Almaden, CA USA

In this paper, we present results of multimodal experimental approaches to study photoresist materials. To build our grasp of EUV photochemistry from the ground up we aim for understanding the whole variety of processes happening after absorption of an EUV photon by a single building block of resist material – a resist molecule. Model photoresist constituent molecules functionalized with halogen atoms, are isolated in the gas phase and exposed to tunable EUV radiation and the direct processes are investigated by photoelectron spectroscopy and photoionization mass spectrometry. We quantify the performance of several candidate molecules in terms of photoemission cross-sections and electron yield per primary photoionization event. We demonstrate that some prototype resist molecules can emit several (photo- and Auger) electrons after single EUV photon absorption. Following the electron emission, the atomic relaxation leads to the molecule fragmentation, which also depends on the halogen functionalization. Secondary electron-driven reactions are studied by tunable electron impact ionization and dissociative electron attachment mass spectrometry. We demonstrate that even very low kinetic energy electrons may lead to the molecule dissociation.

Presenting Author

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

P48

EUV Resist: The Great Challenge of Small Things

S. Castellanos

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EUV lithography is being introduced in the semiconductor industry after a long journey of marvelous engineering and optics improvements in the EUV scanner. Yet, the capture of the EUV projections by the photoresist material remains as a limiting factor in the pattern transfer to the silicon wafer. The need for thin films of materials with a suitable EUV absorptivity together with the complexity of the cascade of chemical events that EUV photons trigger make the optimization of this lithographic process challenging.

In this work an overview on the EUV resists past, present, and future will be given. The performance that has been reported for traditional CAR resists and for novel materials in terms of critical dimension, sensitivity and LER will be reviewed, emphasizing what knowledge on the EUV light-induced chemistry is necessary in order to accelerate their improvement. Current efforts and potential experimental approaches to address these gaps in fundamental understanding of the EUV resists mechanisms will be discussed. The aim of these considerations is to propose a roadmap for EUV resists that helps the EUV lithography community to meet the high volume manufacturing expectations.

Presenting Author

Sonia Castellanos Ortega received her PhD in Chemistry, awarded with an Extraordinary Prize, from the University of Barcelona in 2010 for her work in the design and preparation of organic radicals with applications in electronic devices. During her postdoctoral stage in HU Berlin she conceived novel photoswitchable organic molecules to modulate the rates of light-to-electron conversion in the frame of an Alexander von Humboldt fellowship. Right after, she worked in the development of photoresponsive metal-organic frameworks as a postdoc in TU Delft. Since February 2016 she is the group leader of the EUV Photoresists in the Advanced Research Center for Nanolithography in Amsterdam.

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MTR Resist for Reduced LER in EUV Lithography

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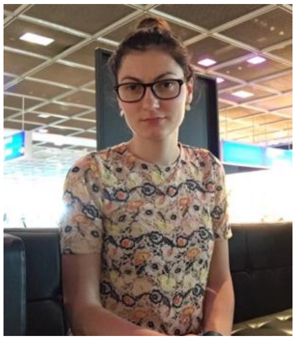
We have previously reported [1] sensitivity enhancement and LER improvement using enhanced versions of our xMT base material. In this study we will present further improvement in the performance of the resist system with the introduction of the next-generation MTR (multi-trigger resist) platform screened at PSI, MET and NXE.

The newly introduced Irresistible Materials MTR resist is designed to address the RLS trade-off issue. This new mechanism enables an intrinsic quenching behaviour to improve resolution and LER at little expense in the sensitivity. The absence of externally added quencher in the system also reduces material stochastics.

The multi-trigger material consists of an MTR molecule and a crosslinker, which together represent the resist matrix, and a photoacid generator (PAG). Upon exposure to EUV photons there will be photoacids generated, as with a chemically amplified resist, which will activate the molecules in the resist matrix. The exposure reaction proceeds as long as a MTR molecule and a crosslinker molecule are simultaneously activated and in close proximity to each other. When these two conditions are not met the resist components will hold on to the acids, and the catalytic reaction will stop. Varying the resist formulation can control this behaviour.

[1] Popescu C., Frommhold A., McClelland A., Roth J., Ekinci Y., Robinson A.P.G, "Sensitivity enhancement of the high-resolution xMT multi-trigger resist for EUV lithography," Proc. SPIE **10143**, 101430V (2017).

Presenting Author



Carmen is a PhD student in the Nano Physics group and in collaboration with the department of Chemical Engineering at the University of Birmingham, UK. Her work is focused on the development of next generation resist materials for EUV lithography. She has a Master degree in Biophysics and Medical Physics.

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EUV Materials Solution

Yoshi Hishiro

JSR

EUV lithography is considered as one of the main drivers to extend Moore’s law toward single digit nanometer technology nodes and has been waited to be practical. This talk will focus on JSR’s EUV materials development concepts and capabilities for stable manufacturing and quality control.

Presenting Author

P54

The Impact of the Sub-Fab on the Availability of EUVL

Anthony Keen

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Availability of lithography tools is critical for end-users in the strive towards high wafer throughput. With the advent of EUVL a new component to the lithography tool facility is introduced in the form of the need for a vacuum and abatement subsystem. Abnormal operation of this subsystem can ultimately have a direct impact on the availability of the process tool, so it is useful to assess its' availability following the recognised standard measurement method. This is captured in the SEMI E10 standard, which establishes a generic way of measuring equipment performance and productivity through the definition of basic equipment states.

To address this Edwards have initiated an availability programme with a view to improving service times (Diagnostics, Access, Replacement and Recovery) and to address equipment reliability. As part of this initiative, an availability matrix was created examining existing scheduled (SD) and unscheduled (USD) down activities to facilitate this objective in accordance with SEMI E10. This presentation will describe some key outputs of this analysis, which has highlighted the need for diagnostics capability and specific system design choices to enable process continuation during maintenance activities as the most important contributors to improving the availability of the vacuum and abatement subsystem.

Presenting Author

Anthony Keen is the Technology Manager – Advanced Lithography Market Sector for Edwards Vacuum. He has been with the company for 16 years.

Anthony joined Edwards to support business growth into emerging markets such as EUV lithography and other vacuum based next generation lithography technologies. He has 25 years experience in the field of vacuum technology covering a broad range of topics, including extensive experience in various surface science and other general gas analytical techniques, such as XPS/UPS, AES, XRD, STM/AFM, IR spectroscopy and mass spectrometry. Before taking up employment with Edwards he worked as a post-doctoral research associate at the University of Nijmegen in the Netherlands (1997 – 2001) in the field of non-linear magneto-optical investigations of thin magnetic films and prior to this gained his PhD at the University of Leicester in the UK (1992 – 1997) in surface science studies of magnetic cluster materials.

P55

Advanced Modeling of Anisotropic Stochastics in EUV Resist

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A major hurdle for advancement of EUV lithography is the development of a thorough understanding of resist patterning phenomena. The combination of photon shot noise and a plethora of other stochastic phenomena ultimately limit the end product of even the most well-resolved aerial images. This paper analyzes the effect of one major source of randomness in the EUVL process: the diffusion of photo-generated acid during post exposure bake (PEB) in chemically amplified resists (CAR). To attack this question, experiments were coupled with stochastic modeling in order to glean insight into acid diffusion mechanisms and parameters.

Two experiments were conducted in order to determine the relationship between bake time and acid diffusion to unexposed areas of resist. In the first, a resist bilayer in was spun onto a wafer. The top layer consisted of a polymer matrix doped with photo acid generator (PAG), while the bottom layer consisted of the polymer matrix only. A blanket exposure thus generated acid in only the top bilayer. Top loss was then measured as a function of bake time. To corroborate this experiment with a more realistic scenario, a wafer was exposed with a line-space pattern. PEBs were then conducted at a variety of times, and the resulting linewidth measured.

The experimental results were used as output targets for a 3D stochastic resist model. In the model, initial PAGs, deprotecting groups, and quenchers are treated as random variables distributed throughout the model's voxels according to a poisson distribution. Additionally, the 2D aerial image is converted into a 3D photon image, first by considering photon absorption in each model layer and then randomizing the photon count according to a poisson distribution. The acid distribution was generated according to the PAG and photon distributions. A reaction diffusion scheme was used to model the PEB and resulting resist profiles, tuning the model parameters to match the experimental data.

Presenting Author

P56

Lateral-shearing Interferometry for High-NA EUV Wavefront Metrology

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As the semiconductor industry advances, the resolution of EUV optical systems becomes higher and higher. Next- generation EUV exposure tools will have numerical apertures (NA) exceeding 0.5, providing an ultimate resolution below 8 nm. However, in order to reach this resolution, the optical aberrations must be characterized and removed.

Lateral shearing interferometry (LSI) has long been a staple of EUV optical testing because it eliminates the need for a high quality reference wave by interfering the test wavefront with shifted copies of itself. So far, LSI has been employed on various EUV systems ranging from small to medium NAs (0.08 - 0.3) with great success [1]. However, when applied to high-NA wavefront metrology, LSI must be reevaluated because the angles of the marginal rays of a high-NA beam interact nonlinearly with diffraction gratings.

To extend LSI to measure EUV wavefronts at high-NA, the first problem is characterizing systematic errors. This task is accomplished via a geometric model known as the “2-ray model” to simulate the systematic errors contained in the LSI interferogram. The construction of the 2-ray model can be divided into the following three parts:

(1) Using the grating diffraction equation to calculate the optical path difference between two rays emitted from the same focus and incident on the same position at detector.

(2) Introducing grating and detector tilts into the model to analyze the tilt-induced systematic errors.

(3) Extending the model to be suitable for aberrated wavefront simulation.

The null interferogram, the interferogram produced by ideal spherical wavefront, contains the systematic errors induced by the grating and the detector. Simulation results using the 2-ray model show that when the grating is parallel with the detector, the aberrations in the null interferogram are minimized. Residual aberrations linearly vary with the distance from the focus to the grating and can be removed by repeating the experiment through focus.

The 2-ray model can be viewed as a linear system and can be used to a basis of sheared Zernike polynomials. A temporal Fourier method is used to extract the shearing wavefront and the final wavefront can be obtained by fitting to this basis.

In summary, a method for lateral shearing interferometry for high-NA EUV wavefront metrology is presented. In this method, the geometric 2-ray model is built, which provides a fast way to characterize the systematic errors and generates a basis of sheared Zernike polynomials suitable for reconstructing the wavefront. This model provides a rigorous understanding of LSI necessary for realizing high-NA EUV wavefront metrology.

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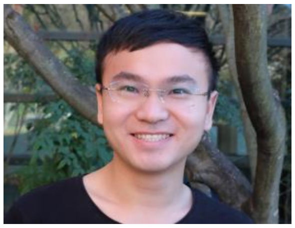
[1] R. Miyakawa, and P. Naulleau, “Extending shearing interferometry to high-NA for EUV optical testing,” In Extreme Ultraviolet (EUV) Lithography VI (Vol. 9422, p. 94221J). International Society for Optics and Photonics (2015).

Presenting Author



Wenhua Zhu received his Bachelor’s in Photoelectric Information Engineering from Nanjing University of Science and Technology in 2014. Then he is pursuing a PhD in Optical Engineering. Now he is an affiliate student at the Center for X-Ray Optics, Lawrence Berkeley Laboratory. Under the direction of Patrick Naulleau, his main research focuses on EUV wavefront metrology.

P61

Advanced Deposition Techniques for Next Generation EUV Mask Blanks

Vibhu Jindal, Abbas Rastegar, Vik Banthia

Applied Materials

The EUV mask blank are composed of multilayer structure consisting of Molybdenum and Silicon, a capping layer, an absorber layer structure, and a backside coating on six-inch square glass substrates with low thermal expansion. While EUV Lithography currently needs reliable supply of high yield and low defect density EUV mask blanks, the high-volume manufacturing at N5 and beyond would need next generation EUV mask blanks with advanced material properties. The paper illustrates the key drivers and critical material properties for next generation EUV Mask Blank. Applied Materials demonstrates significant improvements in different deposition layers in EUV mask blank structure by advanced deposition techniques. The precision materials engineering affects properties including reflectivity, roughness and other important specifications that pave a viable roadmap to meet customer's high-volume manufacturing requirements as opposed to the limitations observed by current manufacturing methods. The paper will further discuss the results on Applied Material's advanced absorber material mitigating mask 3D effects that enables the next generation EUV mask blank for industry.

Presenting Author

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Mask 3D effects First Experimental Measurements with NA 0.55 Anamorphic Imaging

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IMEC, Belgium

High NA (0.55) EUV lithography will be using anamorphic imaging with asymmetric X and Y magnification (4x8). Imaging at higher NA with specific change of light-rays solid angles at mask level will impact the known mask 3D effects. The SHARP EUV actinic mask-imaging microscope at LBNL allows imaging at NA0.55 emulating the relevant solid angles at mask level. It is therefore a nice tool to measure mask 3D effects experimentally in aerial images both at NA0.33 and at NA0.55.

We will discuss under which conditions SHARP can be used to measure mask 3D effects using a dedicated reticle layout and a suited measurement methodology. The comparison of best focus shift through pitch measured on SHARP to rigorous simulations at NA 0.33 gives us confidence in the tool capability and the measurement methodology. The validated methodology enables unique NA0.55 measurements of best focus shift trends through pitch matching with rigorous simulation trends, increasing our confidence both in the experiment and in the simulations at this unexplored high NA EUV imaging.

Presenting Author

Vincent Wiaux received his M.Sc. and Ph.D. degrees in physics from the Université Catholique of Louvain, Belgium, in 1999. He joined imec the same year. Since then he has been involved in lithography imaging, with main focus on Resolution Enhancement techniques, in OPC, and in exploring double patterning using 193 immersion lithography. His current interest is to explore high NA EUV lithography.

P63

EUV Mask Characterization with Actinic Scatterometry

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With EUV Lithography rapidly approaching maturity, accurate metrology to thoroughly characterize EUV photomasks is needed. We present an actinic EUV reflection-based scatterometry technique to measure key parameters of EUV photomasks, including the complex reflection function of the multilayer substrate, along with the absorber thickness and mask dimensions of periodic patterns. Together, these measurements can help predict lithographically relevant light scattering from EUV photomasks, which would provide invaluable feedback in the mask optimization and manufacturing processes. In this paper, we use experimental measurements from the Advanced Light Source and rigorous RCWA simulations to explore the accuracy of dictionary-based reconstruction of these mask parameters under realistic noise and model mismatch conditions, to determine the outlook for this promising technology.

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.

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A SHARP Look at Future Nodes of EUV Lithography

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

CXRO, LBL

The SHARP High numerical aperture Actinic Reticle review Project is a synchrotron-based, 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.

Today SHARP is steadily used for imaging jobs emulating the 3300-generation of EUV scanners. Common tasks include printability studies and repair verification. At the same time we are working on topics geared towards future nodes of EUV lithography. These include imaging at high NA, anamorphic imaging, binary and gray-scale SMO sources and alternative absorber materials.

To facilitate this work, the SHARP microscope uses nanofabricated diffractive imaging lenses that measure less than 100-um in diameter, allowing 100s of lenses to be installed in the tool. Our zoneplate lenses cover a wide range of numerical apertures and pupil shapes. The tool has a lossless Fourier synthesis illuminator, driven by a high brightness beam from the Advanced Light Source. The illuminator readily produces arbitrary source angular spectra.

The paper provides an overview of the SHARP microscope and its key components. A variety of image data is presented, discussing mask 3D effects for anamorphic imaging at high NA and conventional 0.33 NA, comparing two different absorbers. An application example using freeform sources is presented.

Funding for SHARP operations and upgrades is provided by Intel. General EUV infrastructure at Berkeley is funded through the EUREKA program. This research used resources of the Advanced Light Source, which is a DOE Office of Science User Facility under contract no. DE-AC02-05CH11231.

Presenting Author

EUV
Litho, Inc.