2024 Source Workshop

Workshop Abstracts

EUV
Litho, Inc.

Organized By:

Vivek Bakshi (EUV Litho, Inc), Chair

Oscar Versolato (ARCNL), Co-Chair

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2024 Source Workshop Keynote Presentation (Tentative Title)

Jan van Schoot

ASML Netherlands B.V. (The Netherlands)

Presenting Author

Dr. Jan B.P. van Schoot, is Director of System Engineering and Technical Specialist at ASML, based in Veldhoven, The Netherlands. After his study Electrical Engineering (Cum Laude) at Twente University of Technology. He received his PhD in Physics on the subject of non-linear optical waveguide devices in 1994 and held a post-doc position studying waveguide based electro-optical modulators. He joined ASML in 1996 and was Project Leader for the Application of the first 5500/500 scanner and its successors up to 5500/750. In 2001 he became Product Development Manager of Imaging Products (DoseMapper, Customized Illumination). In 2007 he joined the dept of System Engineering. He was responsible for the Optical Columns of the 0.25NA and 0.33NA EUV systems. After this he worked on the design of the EUV source. He was the study leader of the High-NA EUV system and is now responsible for the High-NA optical train. He is a Fellow of the SPIE, holds over 35 patents and presents frequently at conferences about photolithography.
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S2

Solid-State Laser Drivers for EUV Plasma Sources (Keynote Presentation)

Peter F. Moulton

MIT Lincoln Laboratory, Lexington, MA USA

Laser-driven plasmas formed from highly excited tin droplets are the basis for the current generation of EUV, 13.5-nm lithography tools. At the time the tools were first developed, the best laser driver was a pulsed, high-average-power, CO_2 gas laser operating around a 10.6 µm wavelength. Alternate solid state drive sources based on well-developed Nd- or Yb-doped solid state lasers have a much lower conversion efficiency of laser to EUV power. Recent work has shown that mid-IR drive sources in the 2-4-µm wavelength range can provide acceptable conversion efficiencies, approaching if not exceeding that of CO_2 lasers. In this talk, we review the present state of mid-IR solid state laser technology and consider the potential for scaling up the average-power of these devices to the levels required by future EUV lithography sources. We also project how solid state lasers could reduce the overall size, weight and power consumption of present EUV systems.

Presenting Author

Dr. Moulton is a member of the Senior Staff in the Laser Applications and Applications Group at the MIT Lincoln Laboratory. He received an A.B. in Physics from Harvard College in 1968 and M.S. and Ph.D. degrees in Electrical Engineering from MIT in 1972 and 1975 respectively.

Moulton's technical work began in the field of bulk solid state lasers, and in recent years has extended to include nonlinear optics and fiber lasers. At Lincoln Laboratory in 1982 he invented the Ti:sapphire laser, and he has also made important advances in high-power diode-pumped solid state lasers, parametric oscillators, and long-wavelength fiber lasers.

3D Nanotomography via Coherent X-ray Lensless Imaging (Keynote Presentation)

Manuel Guizar-Sicairos

Paul Scherrer Institute, Villigen 5232, Switzerland
Ecole Polytechnique Fédérale de Lausanne, Lausanne 1015, Switzerland

X-rays offer a unique opportunity for 3D high-resolution imaging of buried structures due to both their high penetration and the small wavelength on the order of angstrom. However, reaching nanometer resolution with X-rays poses significant challenges, one being the difficulty in manufacturing efficient X-ray lenses with high numerical aperture.
Coherent X-ray lensless imaging techniques have emerged to circumvent such limitations. These techniques leverage the high coherence of beams, produced by synchrotron X-ray sources, and computational image reconstruction. Using diffraction we can obtain detailed 3D images of the object of interest. Ptychography has seen a particular raise in use around the world due to its reconstruction robustness and applicability large samples [1].

Here I will give an introduction and describe the basic principles of coherent lensless imaging and ptychography, and showcase its application to imaging integrated circuits, for which we have reached a resolution down to 4 nm [2].

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Presenting Author

Manuel Guizar-Sicairos is an Associate Professor of Physics in the Institute of Physics (IPHYS), EPF Lausanne and head of the Computational X-ray Imaging group in the Paul Scherrer Institute, Switzerland. He received his B.Sc. degree in Physics Engineering in 2002 and M.Sc. in Electronic Systems in 2005 from the Tecnológico de Monterrey, Mexico. Received a M.Sc. in Optics in 2008 and Ph.D. in Optics in 2010 from the Institute of Optics, University of Rochester in NY, USA. His research is focused on developing methods and algorithms for high-resolution and 3D computational imaging, in particular using large-scale synchrotron X-ray sources. He is co-recipient of the Innovation Award on Synchrotron Radiation in 2014 and 2021, received the prestigious 2019 ICO prize, and is a Fellow member of SPIE and Optica.

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2024 Source Workshop Keynote Presentation (Tentative Title)

Torsten Feigl

optiX fab GmbH, Otto-Schott-Str. 41, 07745 Jena, Germany

Presenting Author

Torsten Feigl studied physics in Jena, Germany, and in Paris, France. He graduated with a PhD in physics from the University of Jena in 2000. Torsten Feigl joined Fraunhofer IOF in 1994 working on multilayer and grazing incidence optics for the extreme ultraviolet spectral range, soft and hard X-rays. For more than ten years he was leading the "EUV and soft X-ray optics" working group at Fraunhofer IOF Jena. In 2013 Torsten Feigl founded optiX fab, a Fraunhofer IOF spin-off company. Located in Jena, Germany, optiX fab is currently supplying chipmakers, EUV tool and source manufacturers as well as institutes, universities, synchrotron beamlines and EUV research consortia worldwide with customized multilayer and grazing incidence optics for EUV lithography applications at 13.5 nm and the entire XUV, soft and hard X-ray spectral range.

S5

Lithium, a "Dream Fuel" for Actinic Inspection (Keynote Presentation)

Konstantin Koshelev

ISTEQ

It is quite possible that the 13.5 nm Lyman-alpha transition in the spectrum of hydrogen-like lithium ions played a role in choosing the standard for future EUV lithography sources. While it requires sequentially passing through 10 or more ionization stages, investing 500 to 1000 electron volts for creating each emitting ion emitting in the 12-14 nm range, lithium requires only about 80 electron volts to prepare an ion emitting the 13.5 nm line. This apparent "cheapness" hinted on lithium as the "dream fuel." The history of attempts to create an EUV source based on lithium is rich with technological fantasies and ingenious inventions. However, lithium played no practical role in creating industrial EUV sources - lithium plasma demonstrated either very low CE, produced too much "dirt," or possessed both of these "virtues" simultaneously. Most importantly, a rather effective "fuel" was found - tin plasma, where physical constants "played along" in a wonderful way, concentrating few dozen spectral lines of several consecutive ionization degrees of tin atoms in a narrow EUV spectral range.

Researchers' interest returned to lithium when the demand for actinic inspection equipment grew. The zone plates often used in such instruments require high monochromatization of radiation. When using plasma sources based on tin or xenon, such monochromatization leads to significant losses of EUV radiation and limits productivity. Two other high-tech approaches - using high harmonics of laser radiation (HHG) and using synchrotron radiation - either do not yet provide sufficiently high productivity or require changes in the organizational structure of EUV lithography. However, it turned out that a detailed study of the physics of excitation and emission processes of Li+2 Lyman-alpha allows finding a mode of high luminosity of the transition during plasma recombination. The second of the mentioned problems - strong droplet debris - can be solved by using the concept of a rapidly rotating liquid metal target, successfully applied in TEUS (ISTEQ) and URASHIMA (Lasertec) sources. The combination of physical research - modelling and experiments - with engineering art led to the creation of an industrial narrow-band ($\lambda/\Delta\lambda = 1000$) EUV source LEUS, which we present at this conference.

Presenting Author

Konstantin Koshelev is a founder and a Chief of Board of ISTEQ Group from 2014. Graduated Physical-Technical University of Moscow in 1968, PhD on physics in 1975 at Vilnius University, working in a field of plasma radiation (ISAN RAS , Head of Plasma spectroscopy until 2018) and its application in EUV Lithography (EUV Labs, ISTEQ).

S11

Kinetic Simulations of Ion Dynamics in Laser-Driven Tin Plasma EUV Sources (Invited Presentation)

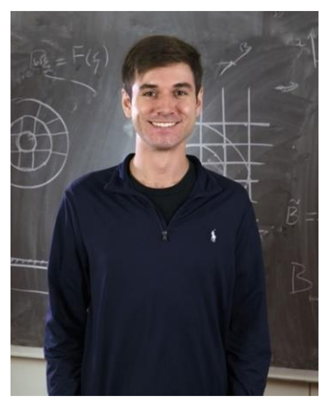
Samuel Totorica

Princeton University, Princeton, NJ 08544, USA

Laser-driven tin plasmas are key to extending Moore's law through the generation of 13.5 nm (+/-1%) narrow-band extreme ultraviolet (EUV) radiation for next-generation lithography. A major challenge in deploying tin plasma EUV sources is protecting sensitive optics from energetic ions produced during the laser-plasma interaction. This study uses fully kinetic particle-in-cell (PIC) simulations to explore ion acceleration mechanisms relevant to tin plasma EUV sources. The interaction of a tin target with an Nd:YAG laser is modeled using an inverse-bremsstrahlung heating operator, with thermal conduction captured via a Monte-Carlo Coulomb collision operator. The simulations track the plasma's evolution from ablation to expansion, allowing detailed analysis of ion trajectories. Comparisons with single-fluid single-temperature radiation hydrodynamics simulations show qualitative agreement over most of the domain but reveal two-temperature features in the PIC simulations due to long thermal equilibration times. The PIC simulations produce a highly collimated group of energetic ions driven by a large-scale electric field from the electron pressure gradient, with differences in the high energy spectrum compared to fluid simulations. These findings have significant implications for improving the modeling of tin plasma EUV sources and developing strategies for debris mitigation.

S. Totorica, K. Lezhnin, D. Hemminga, J. Gonzalez, J. Sheil, A. Hyder, A. Diallo, A. Hyder, W. Fox, "Acceleration Mechanisms of Energetic Ion Debris in Laser-Driven Tin Plasma EUV Sources". Applied Physics Letters 124, 174101 (2024).

Presenting Author



Samuel received his PhD in Physics from Stanford University in 2018 and was then a NASA Jack Eddy Postdoctoral fellow at Princeton University, where he is now an Associate Research Scholar. His research focuses on using particle-in-cell plasma simulations to model kinetic plasma processes in environments ranging from astrophysics to the laboratory. His current focus is using simulations to study the onset of magnetospheric substorms and the associated nonthermal particle acceleration. He is also modelling high-energy-density laboratory astrophysics experiments and studying their connection to systems in space physics and astrophysics. To push the boundaries of kinetic plasma simulation he has been developing the simplex-in-cell simulation method which can reduce the noise associated with simulation particles and improve computational efficiency.

S21

High-Flux XUV Beamlines enabling Photon-hungry imaging and Spectroscopy Methods (Invited Presentation)

Maxim Tschernajew, Vinzenz Hilbert, Oliver Herrfurth, Christian Gaida, Sven Breitkopf, Tino Eidam, Jens Limpert

Active Fiber Systems GmbH, Ernst-Ruska-Ring 17, 07749 Jena, Germany

High-harmonic generation (HHG) driven by ultrashort laser pulses is a well-established method for generating coherent extreme ultraviolet (XUV) to soft X-ray radiation, widely applied in diverse fields. Recent demands from photon-intensive applications such as coherent diffractive imaging, ptychography, semiconductor metrology, and photo-electron spectroscopy have led to the development of more powerful HHG sources with higher repetition rates. Active Fiber Systems GmbH (AFS) has successfully met this need with high-average-power fiber lasers. Following its integration into the TRUMPF group, AFS has adapted its pulse compression technology to TRUMPF's industrial-grade lasers, offering compactness, cost-effectiveness, and scalability. This integration has resulted in an ultra-robust and long-term stable XUV sources, accessible to a broad user base. The photon energy range between 20eV and 150eV can be covered with a single source employing our dual-color driving mode and switchable gas nozzles. The turnkey source provides unprecedented photon flux at the source point of >10^10 photons/s in each harmonic between 80 eV and 140 eV. The brightness is respectively between 200W/(mm^2sr)/1%BW and >1kW/(mm^2sr)/1%BW for the different harmonic lines. Other AFS sources provide an even higher brightness at lower photon energies between 11eV and 80eV. Over the time span of one hour, the photon flux is as stable as ~1% RMS in the spectral range around 70 eV and 120 eV, respectively. Currently further scaling towards >100kW/(mm^2sr)/1%BW is ongoing by using ultrashort pulses at 515nm to very efficiently push the cut-off of these “green harmonics” towards 90eV. We will present the current status of these experiments.

Presenting Author

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

S22

Recent Advances on High-Brilliance EUV Sources based on High - Harmonic Generation (Invited Presentation)

Bastian Manschwetus, Valentina Shumakova, Oscar Naranjo and Robert Riedel

Class 5 Photonics GmbH, Notkestrasse 85, 22607 Hamburg, Germany

With the recent advancement in ultrafast laser technology, the capabilities of laser- based extreme ultraviolet (EUV) and soft-X-ray (SXR) sources have greatly expanded. These coherent and ultrashort sources, based on high harmonic generation (HHG) in noble gases, provide unique opportunities for metrology and advanced material studies as demonstrated by their widespread use in research laboratories and user facilities worldwide. They have the potential to provide deeper insights into the electron dynamics of photoresists and semiconductors, as well as high-brilliance sources for scatterometry and imaging techniques in "at-wavelength" mask and wafer metrology. This progress has been enabled by the combination of state-of-the-art high-power femtosecond lasers with advanced nonlinear technologies, using high-power Yb-doped laser systems and optical-parametric chirped-pulse amplifiers (OPCPA) and multi-pass cells (MPC).

In this contribution, we compare these two laser technologies and discuss their benefits and limitations in the context of HHG. Based on these results, we will present our MEGA-EUV project, which is a collaboration between Class 5 Photonics GmbH, DESY, University of Hamburg, and Amphos GmbH along with partners from semiconductor industry, to scale the output EUV flux to milliwatts and increase strongly the throughput of EUV microchip inspection. A technology demonstrator will be developed using a kilowatt-class Yb laser system to enable high-performance EUV scatterometry at the wavelength of 13.5 nm.

Presenting Author

Bastian Manschwetus, Head of Research and Development EUV/SXR sources, graduated 2010 at the Max-Born Institute Berlin investigating the behavior of atoms and molecules in strong laser fields in his PhD project. With a Marie-Curie fellowship he joined then the group of Pascal Salières at CEA Saclay (France), now diving into the field of attosecond physics by high harmonic generation and atomic and molecular spectroscopy. From 2013, Bastian moved to the Lund Laser Center to work with Nobel price laureate Anne L'Huillier and Per Johnsson on the development of a high peak power EUV source. 2015, he became team leader for the pump probe laser operation at the Free-Electron Laser FLASH in Hamburg. In 2022 he joined Class 5 Photonics as project leader for developing industrial-grade EUV/soft-X-ray sources.

S23

Ultrafast Thin-Disk Amplifiers and Nonlinear Pulse Compression (Invited Presentation)

Thomas Metzger, Catherine Teisset

TRUMPF Scientific Lasers GmbH & Co. KG, Feringastr. 10a, 85774 Unterföhring, Germany

Secondary sources have become critically important for both scientific and industrial applications. They can provide access to new wavelength range via high harmonic generation [1], laser plasma X-ray sources [2] or inverse Compton scattering [3], offering enhanced imaging capabilities in semiconductor lithography or medical tomography. Using laser acceleration [4] compact solutions for targeted medical therapy [5] are also foreseeable. For all those applications, high peak intensities are mandatory to obtain sufficient conversion efficiencies [6] and design cost-effective solutions. In addition, average power is typically desired to reach higher flux enabling rapid data acquisition, treatment, or process. Finally, these driving lasers must be stable and reliable to ensure consistent performance over long periods. Such industrial ultrafast systems are already available from TRUMPF Laser SE delivering 2mJ, 200W, 1ps (TruMicro 6000) to 10mJ, 1kW, 1ps (TruMicro 9000). For even higher pulse energies, the Dira Series from TRUMPF Scientific Lasers is now available with up to 300mJ at 1kHz with <1ps. In recent years, gas-filled multipass cells [7]. became particularly attractive to broaden the spectrum for nonlinear pulse compressions. Combining high optical efficiency, high damage threshold and a robust setup, they emerged as an excellent solution for the compression of sub-ps pulses at high average powers. The generation of shorter pulses which will be highly beneficial for EUV and X-ray sources through a more controlled plasma formation and higher efficiencies. With the HERZ series, we aim at bridging the gap between narrow linewidth Yb-based light sources capable of delivering high average power and broadband Ti:Sapphire with poor power scalability. Recently, we obtained sub-30 fs pulse compression at 10mJ [8], while we demonstrated compressibility at 200mJ down to 50 fs [9]. In parallel, we anticipate the development of industrial systems delivering sub-40fs pulses at the kW-level with tens of mJ.

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Presenting Author

Thomas Metzger studied mechanical engineering at the Technical University in Stuttgart and received his Diploma in 2002. After his degree he worked in 2002 as an intern at Spectra-Physics. During his PhD and as Postdoc in the research group of Prof. Ferenc Krausz at the Technical University in Vienna and at the Max-Planck Institute of Quantum Optics in Garching, he developed ultrafast thin-disk amplifiers in close collaboration with TRUMPF Laser SE. Thomas Metzger has been 2012-2020 CTO and is since 2020 Managing Director of TRUMPF Scientific Lasers GmbH + Co. KG.

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Pulse-Shortening with Multipass Cells

Oleg Pronin, Tomin Joy, Christian Franke, Kilian Fritsch

n2-Photonics GmbH, Hans-Henny-Jahnn-Weg 53, 22085 Hamburg

High harmonic generation strongly benefits from short pulses in the range of <50 fs and or even <10 fs. The industrial grade Yb-based lasers delivering very high average powers >100-1000 W but relatively long pulse durations (200-800 fs) can nowadays be very efficiently shorten with the help of multipass cells and this way boosting the peak power of this lasers by factors 10-20x.

In this work we describe our experiments and ongoing efforts on pulse shortening of different driving lasers such as Light Conversion (Pharos, Carbide), Amphos and Coherent (Monaco). We address challenges appearing when compressing the pulses to <10 fs and <50 fs for different pulse energies raging 0.1 to 3 mJ and input pulse duration 100 fs to 900 fs in combination with high average powers up to 200 W. We present long term stability of these systems (>5 days), short term intensity noise, spectral and pulse duration stability.

We are confident that the technology is ready to be deployed in industrial applications such as high harmonic generation for semiconductor inspection/analysis and hopefully open new applications.

Presenting Author

Oleg Pronin received a Diploma degree in solid-state physics from Moscow Engineering Physics Institute (Technical University) in 2008, and a Ph.D. degree in physics from the Ludwig Maximilian University of Munich, Germany, in 2012 under the supervision of Prof. Ferenc Krausz (2024 Nobel Prize in Physics). From 2012 to 2014, he was a Postdoctoral Scientist with the Ludwig Maximilian University of Munich. From 2014 to 2019, he was a Group Leader at the Max Planck Institute of Quantum Optics, Garching, Germany. Since 2019 he is a full professor at Helmut Schmidt University in Hamburg, Germany. He has co-authored over 30 articles and holds several patents. He is a co-founder of n2-Photonics start-up company.

S25

2μm wavelength fiber lasers for next generation EUV Plasma Sources (Invited Presentation)

Jens Limpert

Institute of Applied Physics, Friedrich Schiller University Jena
Fraunhofer IOF Jena
Active Fiber Systems GmbH, Jena, Germany

The semiconductor industry roadmap is asking for higher and higher EUV power as throughput dictates cost of ownership. The rather low wall-plug efficiency of the currently employed CO_2-drive-laser together with their limited power scalability is considered as one of the main obstacles for further progress. In this context, the wavelength range of 2μm has been identified in recent experimental and theoretical studies as a very attractive spectral region to drive EUV sources based on tin plasma emission [1,2]. The key reasons are: A) the conversion efficiency towards the EUV is on par with that achieved with CO_2-lasers; B) short-wavelength mid-infrared wavelengths can be emitted by solid-state lasers, which offers not only advantages in terms of efficiency and power scalability but also a lower complexity, cost and system foot-print; C) due to the shorter laser wavelength, the etendue of the plasma emission can be better than that achieved with CO_2-drive-lasers.

Thulium, as an emerging dopant in high-power fiber laser systems, emits at a wavelength around 2μm and offers, potentially, a wall-plug efficiency higher than 20%. The presentation will review the current status and scaling potential of Thulium-doped fiber lasers and will present a concept based on an overlap of amplifying multicore fibers to approach Joule-class pulse energy of nanosecond pulses at 50kHz repetition rate and beyond in the short-wave infrared spectral region.

[1] Y. Mostafa, et.al., "Production of 13.5 nm light with 5% conversion efficiency from 2 μm laser-driven tin microdroplet plasma," Appl. Phys. Lett. **4** 123 (23), 234101 (2023).
[2] S. Langer, et.al., "Simulations of laser driven EUV sources—the impact of laser wavelength," 2020 EUVL Workshop (EUV Litho).

Presenting Author

Jens Limpert received his M.S in 1999 and Ph.D. in Physics from the Friedrich Schiller University of Jena in 2003. His research interests include high power fiber lasers in the pulsed and continuous-wave regime, in the near-infrared and mid-infrared spectral range. After postdoc position at the University of Bordeaux, France, where he extended his research interests to high intensity lasers and nonlinear optics, he returned to Jena and is currently leading the Laser Development Group at the Institute of Applied Physics and is head of the business unit “lasers” at the Fraunhofer IOF Jena. He is author or co-author of more than 400 peer-reviewed journal papers in the field of laser physics. His research activities have been awarded with the WLT-Award in 2006, an ERC starting grant in 2009, an ERC consolidator grant in 2013 and an ERC advanced grant in 2019. Jens Limpert is founder of the Active Fiber Systems GmbH a spin-off from the University Jena and the Fraunhofer-IOF Jena.

S31

Recent Progress of Beyond EUV Sources (Invited Presentation)

Takeshi Higashiguchi, Hiroki Morita, Kazuyuki Sakaue, Daisuke Nakamura, Eiji J. Takahashi, Atsushi Sunahara, Gerry O'Sullivan, and Shinichi Namba

Department of Electrical and Electronic Engineering,
Faculty of Engineering, Utsunomiya University,
7-1-2 Yoto, Utsunomiya, Tochigi 321-8585, Japan

We report on some approaches for efficient 13.5-nm EUV sources, such as CO_2 laser irradiation conditions by radiation hydrodynamic simulation (Star-2D) [1] and multiple pulse irradiation experimentally [2]. Improving the EUV conversion efficiency (CE) for a higher-power EUV source has recently been a significant challenge. We simulated that an EUV conversion efficiency of 10% from laser to EUV emission could be achieved with a larger laser spot size, shortened laser pulse width, and longer pre-formed plasma density scale length [1]. The solid-state laser pulse energy is lower than the gas-discharge CO_2 laser under high repetition rate operation at 50 kHz. It would be extremely challenging to use current laser technologies to realize a solid-state laser amplifier with a laser output power of beyond 20 kW. In any case, we again have the limitation imposed by high-power amplifier development for high-power EUV sources. We achieved an EUV CE of 4.7% for oblique laser pulse injection, one of the highest values ever reported, in the case of a 1-mm solid-state laser-produced planar Sn target plasma by multiple laser pulse irradiation [2]. This result suggests that multiple laser-pulse irradiation at a high repetition rate operation could credibly provide the next technology for future high-power EUV sources and exposure tools toward future EUV technology nodes. We can apply this condition for CO_2 and solid-state lasers at 2 – 5 mm wavelengths for EUV & B-EUV sources. We also show the B-EUV spectral narrowing for the B-EUV multi-layer mirror matching with the bandwidth of 0.6% at 6.*x* nm [3] and the angular distribution separation with the ionic debris energy suppression from the Gd plasmas by cross-laser-beam configuration [4]. Finally, we show the recent results for the water-window soft x-ray source experiments as the next feasibility, such as "Blue-X" [5].

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Presenting Author

Takeshi Higashiguchi is a professor. He received his Ph.D. in engineering from Utsunomiya University. His research activities have focused on short-wavelength extreme ultraviolet (EUV & B-EUV at 6.x nm) and water-window soft x-ray sources, laser-plasma interaction, compact high-repetition rate thin-disk lasers, supercontinuum source, vector beam generation and determination of the polarization-state, and medical applications.

S32

Solid state λ ≈ 2 μm laser drivers for EUV lithography (Invited Presentation)

Brendan A. Reagan, Issa Tamer, Zbynek Hubka, Leily Kiani, Jackson Williams, Scott Wilks, Joshua Ludwig, Andreas Kemp, Jason Owens, Andrew Church, František Batysta, Thomas Galvin, Drew Willard, Andrew Yandow, Justin Galbraith, David Alessi, Colin Harthcock, Brad Hickman, Candis Jackson, James Nissen, Sean Tardiff, Hoang Nguyen, Robert Plummer, Emily Sistrunk, and Thomas M. Spinka

Lawrence Livermore National Laboratory, Livermore, CA, USA

Recent progress in the development of efficient and compact diode-pumped, solid state λ ≈ 2 μm Tm:YLF lasers will be presented. Recent experimental results include the demonstration of a compact chirped pulse amplification laser system producing Joule-level, 1 TW peak power, femtosecond laser pulses [1]. Additionally, the generation of 1 kHz bursts of broad bandwidth 1 J pulses, >20 J, nanosecond duration pulses, and the production of quasi-steady-state, high repetition rate bursts of nanosecond duration pulses with 19% optical-to-optical conversation will be discussed [2]. Applications of these lasers include the compact laser-driven acceleration of electrons and muon generation for novel imaging. Finally, the prospects of applying Tm:YLF-based lasers to drive future λ=13.5nm and shorter wavelength EUV sources for lithography and future research and development directions will be presented [3].

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[1] I. Tamer, et al., "Demonstration of a 1 TW peak power, joule-level ultrashort Tm:YLF laser," Opt. Lett. **49**, 1583-1586 (2024).

[2] I. Tamer, et al., "1 GW peak power and 100 J pulsed operation of a diode-pumped Tm:YLF laser," Opt. Expr. **30**, 46336-46343 (2022).

[3] B. A. Reagan, et al., "Solid state 2-μm laser drivers for EUV lithography," Chapter 23 in Photon Sources for Lithography and Metrology, SPIE Press, Bellingham, Washington, pp. 999–1025 (2023).

Presenting Author

Brendan Reagan has been laser physicist at Lawrence Livermore National Laboratory since 2018 and is a group leader in the Advanced Photon Technologies program in the NIF and Photon Science Directorate. His research focuses on the development of high energy, high average power laser systems and their applications to novel radiation sources. Prior to joining LLNL, he was a research scientist in the Department of Electrical and Computer Engineering at Colorado State University. He completed his PhD in Electrical Engineering at Colorado State University in 2012 with research focused on the development of high energy, short pulse, diode-pumped solid state lasers. He has coauthored papers and given invited conference presentations on these lasers and their applications including driving high repetition rate, compact plasma-based soft x-ray lasers and incoherent sources of extreme ultraviolet radiation.

S33

A Path to 2000 W
(Invited Presentation)

Kevin Heidrich

xLight Inc, 380 Portage Ave, Palo Alto CA 94306

Current high volume and development EUV scanners are working with a limited light budget requiring compromises in patterning integrity and system productivity. To enable high power and overcome the limitations of the industry, xLight have been working toward an industrial scale FEL to enable light-as-a-utility for next generation lithography. xLight have overcome significant engineering challenges from past FEL designs to enable a distributed and scalable EUV source. Enabling high dose patterning for both improved productivity and stochastics requires optimization through the entire photon lifecycle. xLight have designed an FEL multiplexing system, a robust transport system from the facility to the scanners, and scanner integration module, all working to enable high intermediate focus power. xLight will enable 1 kW power at intermediate focus from a starting source power of 6 kW per system. Subsequent optimizations in the scanner illumination system can further utilize the diffraction-limited etendue of the FEL EUV source to enable 2 kW at intermediate focus equivalent power while reducing the FEL source power to 5.3 kW per system.

Presenting Author

Kevin Heidrich has worked in the semiconductor industry for 28 years with a focus on semiconductor process and process integration, capital equipment, manufacturing systems, and related products and services. Kevin was formerly employed at Onto Innovation (the merger of Nanometrics Inc and Rudolph Technologies in 2019) holding the title of SVP, Corporate Development & Marketing.

Prior to Onto, Kevin was employed at Nanometrics Incorporated, from April 2006 holding the title of SVP Marketing & Business Development. He was responsible for product marketing, corporate strategy, and M&A. Kevin began his career working in process engineering at Intel Corporation and spent 10 years working in Intel's Logic Technology Development group in Portland Oregon.

S34

Grazing Incidence Optics Calculations for Plasma and 6.xx nm Coherent Beams (Invited Presentation)

Ladislav Pina

*Rigaku Innovative Technology Europe,
Dolni Brezany 868, 25241 Prague, Czechia*

In this presentation I will cover research advances in grazing incidence optics (GIXO) design and calculations. Typical examples of grazing-incidence X-ray mirror systems based on single and double reflection are described, including modelling of optical performance, effects of surface figure errors, micro-roughness, and actual performances and applications in laboratory. In connection with X-ray mirror design and manufacturing three internal software packages have been designed during several past years. A software package for rotational ellipsoid (RE)-type optics geometry calculations, software package for rotational Wolter (RW)-type optics geometry calculations, and software package for rotationally symmetric arbitrary-freeform optics raytracing calculations. GIXO calculation for 6.xx lambda is presented as an actual example.

Presenting Author

Ladislav Pína received M.Sc. and Ph.D. degrees from the Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, in 1972 and 1978, respectively. From 1980 to1981, he was a postdoctoral fellow at the Department of Pure and Applied Physics of the Queen's University of Belfast which included experimental work using ion and X-ray diagnostics of laser plasma in Rutherford Appleton Laboratory. In 1983, he started to work with the Department of Physical Electronics as A. Professor and has been teaching electricity and magnetism, quantum electronics and X-ray physics. He supervises MSc. and PhD students. His research interests include physics of generation, detection and imaging in EUV to X-ray radiation bands. A.Prof. Pina is CEO of Rigaku Innovative Technology Europe in Prague. He is a member of SPIE.

S35

Industrialization of Laser-driven Accelerators and Light Sources (Invited Presentation)

B. Manuel Hegelich

TAU Systems Inc. & University of Texas at Austin

Recent years have seen significant advances in laser-driven accelerator systems in terms of reliability and reproducibility as well as in terms of bunch energy, charge and emittance. At UT Austin we have investigated and developed the underlying scientific principles. At TAU Systems, Inc., we aim to integrate those advances into a single system, allowing a transition from the laboratory to the market. As a first step, we are opening TAU Labs, a Beam time-as-a Service application center for laser-driven beams and lightsources, opening in 2025. We will present a progress update on its build out, commissioning and capabilities. We well also present recent results on laser-driven particle acceleration and their application for semiconductor metrology and lithography in the EUV, beyond EUV and X-ray spectral regions. We will show recent advances in implementation of wakefield technology, first results on laser-driven FEL, as well as recent progress on smaller, compact high repetition rate systems and a laser-based light source service center.

Presenting Author

Prof. B. M. Hegelich is the founder and CEO of TAU Systems Inc., an Austin, TX based Deep Tech company, developing and commercializing laser-driver particle accelerators and EUV/x-ray light sources for semiconductor-, battery- and medical applications. He is a professor at the University of Texas at Austin, leading the research group for Relativistic Quantum Photonics and one of the pioneers of laser particle acceleration. His research includes advanced particle and x-ray sources, high power lasers, nuclear fusion, and quantum effects in intense fields. Dr. Hegelich led research groups Los Alamos National Laboratory, South Korea's Center for Relativistic Laser Science and was appointed Visiting Professor and Fellow at the Center for Advanced studies at the LMU München. Dr. Hegelich received his B.S. degrees from University of Siegen and Napier University Edinburgh, his M.S. degree from the University of Göttingen and his PhD from LMU München and the Max-Planck-Institute for Quantum Optics. His research groups hold the records for the highest electron and ion energies generated with a laser.

S36

2024 Source Workshop - Invited Presentation (Tentative Title)

Marcelo Ackermann

University of Twente

Presenting Author

Marcelo Ackermann is chair of the Industry Focus Group – X-ray and EUV (XUV) optics at the MESA+ institute of the University of Twente. He obtained his PhD in physics (cum laude) in 2007 on a shared research project between Leiden University and the ESRF in Grenoble, under the guidance of Prof. Frenken and Prof. Ferrer. After that he held different leading positions in industrial research for the development of X-ray, visible and IR optics at cosine Research, Helbling Technik, SCHOTT Advanced Optics and ASML. In 2020 he re-joined academia as full professor in the XUV group, focusing on the development of next generation reflective, refractive and transparent X-ray and EUV optics in collaboration with industrial partners like Zeiss, ASML and Malvern Panalytical.

S41

Effect of Target Mass on CO_2-driven EUV Emitting Tin Plasma for Nanolithography

J. Gonzalez[1], J. Sheil[1,2]

[1] *Advanced Research Center for Nanolithography, Science Park 106, 1098 XG Amsterdam, The Netherlands*
[2] *Department of Physics and Astronomy, and LaserLaB, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*

State-of-the art nanolithography for the semiconductor industry employs Extreme Ultraviolet (EUV) light generated by illuminating tin targets with a CO_2 laser [1]. The resulting high charge state plasma (Z > 10) has a significant emission in the 13.5 nm ± 1% band [2,3] in which the Mo/Si mirrors used to guide the light towards the wafer have a peak reflectivity. These tin targets start as droplets of ~30 μm in diameter, which are deformed by a laser pulse into thin disks of ~200 μm of radii and thicknesses of ~50 nm. During this deformation process, between half and three-quarters of the initial droplet mass is lost due to fragmentation [4]. This results in less mass available to form the EUV in-band emitting plasma with the CO_2 laser. In this work, we quantify the effect of the available mass on the emission of in-band light in EUV sources for nanolithography [5]. Two-dimensional rad-hydrodynamic simulations performed with the RALEF-2D code [6] are presented. A distinct trend of increasing conversion efficiency (CE) of laser energy into in-band energy with a higher target mass is identified. We find that the maximum CE is obtained when the target *feeds* mass to the plasma during the whole pulse. A sweep in laser energy shows that overheating the plasma for cases with more than 50% of the droplet mass increases the in- band energy emitted without a significant drop in CE.

[1] J. Fujimoto *et al.*, Journal of Micro/Nanolithography, MEMS, and MOEMS, **11**(2), 021111 (2012)

[2] O. O. Versolato, Plasma Sources Science and Technology, **28**(8), 83001 (2019)

[3] I. Fomenkov et al., Advanced Optical Technologies, **6**(3), 173 (2017)

[4] B. Liu *et al.*, *Journal of Applied Physics*, **129**(5), 053302 (2021)

[5] J. Gonzalez, J. Sheil, *Phys. Plasmas* **31**(5): 050701, (2024).

[6] M. M. Basko, "RALEF-2D: A 2D hydrodynamic code with heat conduction and radiation transport. II. Solution of the radiation transfer equation." Darmstad: GSI (2009)

Presenting Author

Jorge Gonzalez got his PhD in Aerospace Engineering at the Technical University of Madrid in 2017 with 'cum laude'. His work dealt with the kinetic simulation of low-temperature plasma for space propulsion and plasma diagnosis with a semi-analytical method. Since then, Dr. Gonzalez has worked in fluid and kinetic modelling of plasma and its interaction with neutrals for space propulsion, edge plasma in fusion devices and, currently, laser- plasma interaction for lithography sources.

S42

Electron capture in collisions of Sn ions with H_2 molecules

K. Bijlsma[1,2], Emiel de Wit[1,2], L. Tinge[1,2], L. Assink[1,2], L. Oltra[3], I. Rabadán[3], O.O. Versolato[2], L. Méndez[3] and R. Hoekstra[1,2]

[1]Zernike Institute for Advanced Materials, University of Groningen, The Netherlands
[2]Source Department, Advanced Research Center for Nanolithography, The Netherlands
[3]Departamento de Química, Universidad Autónoma de Madrid, Spain

We report on our studies of electron capture in collisions of Sn^{q+} (q=2-4) ions with molecular hydrogen, among which the work of [1]. Cross sections for these processes are important for ion mitigation models for Sn-LPP-based EUV sources, as energetic Sn^{+} ions are stopped better than Sn^{2+} ions by a H_2 buffer gas [2]. Our measurements are performed at the ZERNIKELEIF facility using a crossed-beam type experiment of a decelerated Sn ion beam and an H_2 gas jet. Charge-state resolved Sn ion numbers are measured with a retarding field analyzer. Both single and double electron capture cross sections have been measured. We will show our methods and results and discuss the possible origins of the observed behavior. We also compare our experimental results to Landau-Zener and semiclassical calculations.

[1] Bijlsma et al., *Atoms* ***12,*** 9 (2024).

[2] Abramenko et al., *Appl. Phys. Lett.* **112**, 164102 (2018).

Presenting Author

Emiel de Wit is a PhD candidate working in the Ion Interactions group at the University of Groningen since 2023, after completing his master’s degree with the same group. His research is focused on measuring the electron transfer and stopping processes in collisions of multiply charged Sn ions with molecular hydrogen.

S44

Investigation of Laser-plasma Interaction in a Dual-pulse Laser - produces Tin Plasma (Invited Presentation)

Yiming Pan[1], Kentaro Tomita[1], Atsushi Sunahara[2], Katsunobu Nishihara[3,4], Akira Sasaki[5]

1 Division of Quantum Science and Engineering, Graduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-ku, Sapporo, Hokkaido 060-8628, Japan
2 Center for Materials Under eXtreme Environment (CMUXE), School of Nuclear Engineering, Purdue University, 500 Central Drive, West Lafayette, IN 47907, USA
3 Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, Osaka, 565-0871, Japan
4 Faculty of Engineering, Osaka Metropolitan University
5 Kansai Institute for Photon Science (KPSI), National Institutes for Quantum Science and Technology (QST), 8-1 Umemidai, Kizugawa-shi, Kyoto 619-0215 Japan

Early in the development stage of EUV-LPP source it was realized that high CE and low debris could be both obtained in a double pulse (DP) scheme. Recently, a record-high CE of 4.7% was reported[1]. However, the interaction between the laser and pre-plasma remains poorly understood, despite its crucial role in further optimizing DP-driven EUV sources. In this study, we investigate the laser-preplasma interaction in a Sn-LPP produced by the double pulse (DP) regime at multiple delay times between the pre- and main-pulse. ne and Te are characterized in both the pre-plasma and the plasma reheated by the main pulse. The experimental results will also be used to validate the STAR2D simulations.

[1] T. Sugiura, Appl. Phys. Lett. 125, 034103 (2024)

Presenting Author

Yiming PAN received his PhD degree in Department of Applied Science for Electronics and Materials from Kyushu University, 2023. Currently he is a postdoctoral researcher in Faculty of Engineering, Hokkaido University, supported by JSPS fellowship. His research in focused on plasmas for various industrial applications and laser diagnostics of those plasmas.

S45

Pulsed EUV induced plasma: fast transients, accumulation and hybrid 3D-PIC model (Invited Presentation)

Mark van de Kerkhof, Efe Kemaneci, Luuk Heijmans, Andrei Yakunin

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

EUV lithography has been adopted worldwide for High-Volume Manufacturing (HVM) of sub-10nm node semiconductors. EUV light is generated by a pulsed Laser-Produced Plasma (LPP) Source, with ~100 ns of EUV light every 20 µs. This in turn induces a pulsed plasma in the scanner as the photons travel through the low-pressure scanner background gas. The photo-ionization creates high-energy electrons (up to ~80 eV) during the actual EUV pulse (~100 ns) and the electron energy distribution will deviate significantly from thermal equilibrium. Between pulses (~20 µs), the plasma cools down and diffuses towards the walls. Subsequent pulses will lead to plasma accumulation, resulting in a quasi-steady-state low-temperature plasma with periodic transient peaks in ion energy and flux.

This requires a tailored modeling approach, where no a-priori assumptions can be made about the electron and ion energy distribution functions. A 3D Particle-in-Cell (PIC) Monte-Carlo model has been developed, which has been hybridized to allow a rigorous modeling of the transients during the EUV pulse, while switching to Fluid model mode for the cold decay phase to reduce the calculation time. The resulting Hybrid 3D-PIC model allows modeling the large 3D scanner volume over multiple pulses without losing physical accuracy.

This presentation will discuss relevant details of the 3D-PIC model, and validation of the model on an LPP test system.

Presenting Author

Mark van de Kerkhof received an PhD in Plasma Physics from Eindhoven University of Technology. He began his career at ODME, and in 1999 joined ASML, working on development of sensors as well as projection optics for both DUV and EUV. He currently is Director for EUV projects at ASML Research. He holds over 100 patents and authored or co-authored more than 50 scientific papers. He is a Fellow of SPIE.

S46

Laser Plasmas Interactions for Microelectronics: Status Update (Invited Presentation)

Ahmed Diallo

Advanced Research Projects Agency-Energy (ARPA-E)

The Princeton Plasma Physics Laboratory (PPPL) is expanding its efforts to plasma applications for micro-electronics, leveraging its comprehensive expertise in plasma modeling, kinetics, magnetics, diagnostics, and high energy density science. With a focus on innovation, PPPL is leveraging the advanced particle-in-cell code PSC and the radiation-hydrodynamics code FLASH. Alongside the commissioning of an on-site laboratory, these tools will empower PPPL to develop predictive capability. This initiative aims to revolutionize plasma sources of extreme ultraviolet (EUV) radiation, thereby opening new realms of possibility in plasma technology. As part of this endeavor, PPPL is embarking on a project to enhance the efficiency and minimize the debris in laser-driven tin (Sn) sources of EUV. This project will not only leverage PPPL's unique diagnostic tools but also plans to integrate the specialized capabilities of other universities and national laboratory partners. In this talk, I will provide a status update on the commissioning of the onsite laboratory.

Presenting Author

Dr. Ahmed Diallo is a Program Director at the Advanced Research Projects Agency-Energy (ARPA-E), where he advances commercial fusion energy by guiding and overseeing transformative research projects. At Princeton Plasma Physics Laboratory (PPPL), he served as Principal Research Physicist and the Head of the Advanced Diagnostics Development Division. During his tenure at PPPL, Diallo developed advanced lasers, X-rays, and other diagnostic techniques in support of microelectronics, quantum computing, high-energy-density plasmas, and magnetic fusion plasma research. He also served as the Deputy Director for the public-private Innovation Network for Fusion Energy partnership, where he planned, directed, and evaluated research activities in partnership with national labs, universities, and private industries. While at PPPL, Diallo was a recipient of the U.S. Department of Energy's Early Career Research Program Award, was honored as a DOE Oppenheimer Fellow, and was named a PPPL Distinguished Research Fellow. Prior to his time at PPPL, Diallo served as a Research Fellow at the Australian National University, and as a Post-Doctoral Scientist at the Swiss Plasma Center at the Swiss Federal Technical Institute. He holds a Ph.D. in physics from the University of Iowa.

S47

Laser-produced Tin droplet Plasma Interference Diagnosis and Droplet Deformation Study

Wang Xinbing *, Qi Huiming, Sun Qin, Zuo Duluo

Wuhan National Laboratory for Optoelectronics, Huazhong University of Science & Technology, Wuhan 430074, China.

We report results from the optical interferometric diagnosis of a laser-produced tin droplet plasma for the extreme ultraviolet (EUV) light source. Nomarski interferometry was utilized to obtain the spatial distribution of electron density. To mitigate the plasma's heating and suppress plasma background radiation, we employed the low-power CW probe laser and narrow-band filter in our experiment. A shadowgraph technology is used to investigate the laser-droplet impact deformation. By utilizing the combination of multiple dichroic mirrors, droplet detection, synchronization of laser with droplet, and droplet deformation in two direction can be realized in very compact design. Particularly, sheet-like targets in side-view and disk-like targets in front-view shadowgraphs are observed at the same time. In addition, the dynamic evolution of the droplet deformation process is presented, keeping consistent with the prediction of the theoretical model.

Presenting Author

Wang Xinbing received the B.Sc. degree from Nanjing Institute of Technology, Nanjing, China, in 1987, the M.Sc. degree from Southeast University, Nanjing, in 1990, and the Ph.D. degree from the Huazhong University of Science and Technology (HUST), Wuhan, China, in 1997. He is currently a Full Professor with Wuhan National Laboratory of Optoelectronics (WNLO), HUST. His research interests include laser-produced plasma, tin droplet generator, extreme ultraviolet source, laser sustained plasma, and plasma diagnosis.

S48

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

[1,2] Hakaru Mizoguchi, [3]Kentaro Tomita, [1]Daisuke Nakamura,[1]Yukihiro Yamagata, [4]Takeshi Higashiguchi, [5]Atsushi Sunahara, [7]Katsunobu Nishihara, [1] Takashi Toshima,[1]Hiroki Kondo, [1]Takuji Sakamoto, [1]Tanemasa Asano and [1]Masaharu Shiratani

1. *Quantum and Photonics Technology Research Center, Graduate School of Information and Electrical Engineering, Kyushu University,744 Motooka Nishi-ku Fukuoka 819-0395, Japan*
2. *Gigaphoton Inc., 400 Yokokurashinden, Oyama-shi, Tochigi, 323-8558, Japan*
3. *Division of Quantum Science and Engineering, Graduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-ku, Sapporo, Hokkaido 060-8628, Japan.*
4. *Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Kasuga, Fukuoka, 816-8580, Japan*
5. *Center for Materials Under eXtreme Environment (CMUXE), School of Nuclear Engineering, Purdue University, 500 Central Drive, West Lafayette, IN 47907, United States of America*
6. *Utsunomiya Univ.*

Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, 565-0871, Osaka, Japan

In this conference, we will report about new EUV research activity in Kyushu-Univ. in Japan. We have been planning EUV Exposure Research Center for support material development and also new high power EUV source investigation program has been on going. It's trigger is donation of 30kW CO2 driver laser system from Gigaphoton Inc. in 2022.

On the other hand, recent progress of LPP EUV light source is remarkable. Ten years ago, power level is only several 10 W level. At present 250W power level is realized in semiconductor mass production factories1) by ASML. However pioneer of this Unique technologies including; combination of pulsed CO2 laser and Sn droplets, dual wavelength pico second laser pulses for shooting and debris mitigation by magnetic field have been applied by Gigaphoton 2). They have demonstrated high average power >300W EUV power with CO2 laser more than 27kW at output power in cooperation with Gigaphoton and Mitsubishi Electric 3) until 2018. In near future more higher power (>600W) EUV source is required to fit High NA (>0.55) lithography of semiconductor industry.

In this paper we will discuss about the Sn plasma dynamics which dominate the EUV emission by using Thomson Scattering (TS) measurement4). Recent TS results have revealed whole profiles of electron temperature and ion density in the EUV sources. These results mention that there is still sufficient potential to increase EUV output power and conversion efficiency in near future. This conceptual investing encourage us to improve EUV Light Source performance.

1) Michael Purvis, Igor Fomenkov, Alexander Schafgans, Mike Vargas, Spencer Rich, Yezheng Tao, Slava Rokitski, Melchior Mulder, Erik Buurman, Michael Kats, Jayson Stewart, Andrew LaForge, Chirag Rajyaguru, Georgiy Vaschenko, Alex Ershov, Robert Rafac, Mathew Abraham, David Brandt, Daniel Brown:" Industrialization of a robust EUV source for high-volume manufacturing and power scaling beyond 250W" Proc. SPIE. 10583, Extreme Ultraviolet (EUV) Lithography IX (2018)
2) Yoshifumi Ueno, Hideo Hoshino, Tatsuya Ariga, Taisuke Miura, Masaki Nakano, Hiroshi Komori, Georg Soumagne, Akira Endo, Hakaru Mizoguchi, Akira Sumitani, Koichi Toyoda : 'Laser produced EUV light source development for HVM', Proc. SPIE 6517 (2007) .
3) Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Krzysztof M. Nowak, Yasufumi Kawasuji, Hiroshi Tanaka, Yukio Watanabe, Tsukasa Hori, Takeshi Kodama, Yutaka Shiraishi, Tatsuya Yanagida, Tsuyoshi Yamada, Taku Yamazaki, Shinji Okazaki, Takashi Saitou.:" Performance of 250W High Power HVM LPP-EUV Source", Proc. SPIE 10143, Extreme Ultraviolet (EUV) Lithography VIII (2017)
4) Kentaro Tomita, Yuta Sato, Syouichi Tsukiyama, Toshiaki Eguchi, Kiichiro Uchino (Kyushu Univ.) Kouichiro Kouge, Hiroaki Tomuro, Tatsuya Yanagida, Yasunori Wada, Masahito Kunishima, Georg Soumagne, Takeshi Kodama, Hakaru Mizoguchi (Gigaphoton Inc.), Atsushi Sunahara and Katsunobu Nishihara (Osaka Univ.), "Time-resolved two-dimensional profiles of electron density and temperature of laser-produced tin plasmas for extreme-ultraviolet lithography light sources" Scientific Reports

Presenting Author

Hakaru Mizoguchi is a Guest Professor of Kyushu University. He was Senior Fellow of Gigaphoton Inc. He is Fellow of The International Society of Optical Engineering (SPIE), and member of The Laser Society of Japan and The Japan Society of Applied Physics.He received a diplomat degree in plasma diagnostics field from the Kyushu university, Fukuoka, Japan in 1982 and join Komatsu ltd.. He joined CO2 laser development program in Komatsu for 6 years. After that he was 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 development with present position. He got Sakurai award from OITDA Japan in 2018, and IAAM Scientist Award in Advanced Materials Lecture Series 2020.

Plasma-particle Interaction under Conditions Relevant to EUV Lithography (Invited Presentation)

Job Beckers

Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, the Netherlands

Once nano to micrometer-sized particles are immersed in plasma, they obtain an electrical surface charge. Depending on the conditions of the surrounding plasma, the material and surface conditions of the particles, and the possible presence of (ionizing) background radiation, the sign of this charge may be positive or negative. Moreover, the residual charge may significantly vary spatially and/or temporally.

With the eye on preventing and controlling contamination of ultra-clean near-vacuum systems, e.g. Extreme Ultraviolet (EUV) lithography scanners, exploring and understanding the interactions contaminating particles have with their (plasma-)surroundings is of utmost importance as such interactions may affect processes like particle transport, particle (re-)mobilization, and particle fragmentation and morphology change [1-3]. Hence, an enhanced understanding of plasma-particle charging, and other plasma-particle interactions may enable the development of new in-situ contaminating mitigation strategies.

This contribution will present some of our latest results and insights regarding plasma-particle interactions under conditions relevant to EUV lithography.

[1] J. Beckers et al., *Phys. Plasmas* 30, 120601 (2023); https://doi.org/10.1063/5.0168088
[2] M. van de Kerkhof et al., *Proc. SPIE 12953, Optical and EUV Nanolithography XXXVII, 129530E* (2024); https://doi.org/10.1117/12.3009896
[3] D Shefer et al., *J. Phys. D: Appl. Phys.* 56 455201 (2023); https://doi.org/10.1088/1361-6463/aceb02

Presenting Author

Job Beckers holds the position of Associate Professor at the Eindhoven University of Technology (TU/e). In 2007, he obtained his MSc degree in Applied Physics from TU/e and in 2011 he obtained his PhD degree Cum Laude on the topic of "dust particle(s) (as) diagnostics in plasma" from the same university. After his PhD, Beckers worked at the company XTREME Technologies (Aachen Germany) for a year on the development of an EUV light source for EUV lithographic applications before being appointed at TU/e. In June 2017, he was awarded the prestigious NWO VIDI grant.

S50

Spectroscopic Imaging of Tin Gas Vaporized Near Plasma Threshold

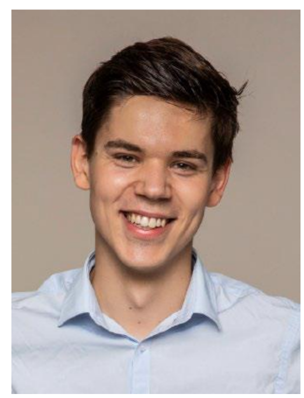
D. J. Engels, H.K. Schubert, M. Kharbedia, W. Ubachs, and O.O. Versolato

ARCNL, Science Park 106, 1098 XG Amsterdam

We investigate tin vapor created from a thin film after irradiation by a laser pulse; a case inspired by EUV generation for state-of-the-art nanolithography. We investigate such a tin vapor using 5-ns time-resolved high-resolution spectroscopic imaging, a previously developed method [Engels et al. Appl. Phys. Lett. **123**, 254102 (2023)]. This method results in a spatially resolved spectrum with a 40 µm spatial and 10 cm^{-1} spectral resolution.

We use the method to study vapors created by vaporizing at different laser intensities. We find that the atomic resonances of neutral tin remain, while the broadband contribution from nanoparticles disappears at the highest intensity. We also show that the temperature rises from 3000 K to 8000 K at the highest intensity used. With the current studies we demonstrate the applicability of the spectroscopic imaging method also in the regime of plasma generation in high-density vapor.

Presenting Author



Dion Engels is a Ph.D. candidate in the EUV Plasma Processes group of ARCNL since August 2022. He studies 2µm-driven laser- produced-plasmas for EUV production. Additionally, he is involved the 'target shaping' studies at ARCNL, focusing on studying tin vapor spectroscopically. He started with this last topic during his Master thesis, which he did at ARCNL for his double Master's degree in Applied Physics and Nuclear Fusion at the Eindhoven University of Technology. His Master thesis was chosen as the best Master thesis from Applied Physics for that year.

S51

Power Partitioning Reconstruction for Laser Produced Plasmas

D.J. Engels, F. Kohlmeier, E.J. Salumbides, Y. Mostafa,
W. Ubachs, O.O. Versolato

ARCNL, Science Park 106, Amsterdam, The Netherlands

We are investigating if 2μm solid-state drive lasers could be used for future EUV sources. Previously, we have demonstrated a high conversion efficiency (up to 5%) from laser light into in-band EUV using this laser wavelength. In this work, we study the partitioning of the input laser energy into different sinks of the laser produced plasma. We use our self-developed high energy 2μm laser system together with an extensive setup of diagnostics. The photonic plasma emissions are measured using EUV photodiodes and a wide-range spectrometer; the ionic emissions are measured with a set of retarding field analyzers. Energy carried by neutral and laser transmission and reflection is also estimated. Combining these tools, we can reconstruct the power partitioning of the laser light into the main sinks of the laser produced plasma in great detail.

Presenting Author

Felix Kohlmeier is a PhD candidate at ARCNL. He completed his Master in Physics at the University of Grenoble and the Karlsruhe Institute of Technology in 2023. Since November 2023, he has been working in the EUV plasma processes group of ARCNL on the topic of laser produced plasmas for EUV production.

S61

Next-Generation Discharge-Produced Plasma (DPP) EUV Source (Invited Presentation)

David Reisman[1], Daniel Arcaro[1], Nick Lubinsky[1], Kosuke Saito[2], Fred Niell[3], Mike Roderick[1], Aaron Feldman[1], Chris Lee[1]

[1]Energetiq Technology, Inc., Wilmington, MA 01887, USA
[2]Hamamatsu Photonics K.K. , Japan
[3]Nielltronix Inc., Tampa, FL 33609, USA

Energetiq Technology's EQ-10 Electrodeless Z-Pinch™ EUV light source uses a xenon plasma Z-pinch to produce 13.5 nm (±1% BW) radiation with an EUV power of ~20W. In this talk, we will present the next-generation EUV source called "EQS-10," which enables an EUV power of >40W. To solve technical challenges resulting from Xe fueling starvation at high frequency and demands for increased power input into the plasma, we developed new technologies such as Xe direct-fueling and FET-based high voltage switching. We also developed a pre-ionization scheme that optimizes the plasma prior to the main pinch initiation, thus enabling high conversion efficiency. Using the new source, we have generated a smaller (FWHM <300 μm), more elliptical-shaped plasma to enable high-NA collection. Experimental data, as well as theoretical considerations and various simulation results, will be presented.

Presenting Author

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

S62

Development Progress of Gigaphoton's Sn-LPP EUV Light Source for Inspection Systems (Invited Presentation)

Fumio Iwamoto, Yoshifumi Ueno, Shinji Nagai,
Kenichi Miyao, Hideyuki Hayashi, Takuya Ishii, Tamotsu Abe,
Hiroaki Nakarai and Takashi Saito

Gigaphoton Inc.
400 Yokokura Shinden, Oyama-shi, Tochigi, 323-8558, JAPAN

Advanced semiconductor factories around the world widely use EUV lithography and EUV mask inspection tools. Actinic EUV mask inspection tools require EUV light sources with high brightness, high availability, and high reliability. Gigaphoton Inc. has been developing a laser-produced plasma (LPP) EUV light source using Sn droplet method since 2002. Based on our accumulated high-power LPP technologies, we have developed a Sn-LPP EUV light source for inspection systems. This light source uses a minimum-mass Sn droplet generator with an in-line Sn fuel supply system, a double-pulse laser irradiation scheme with precise shooting control and a debris mitigation technology with H_2 buffer-gas flow. During 3000 hours of continuous operation, a brightness of 120W/mm^{2}sr at the plasma point and a stable EUV energy 3σ-value below 5% have been obtained. It was confirmed that even after nearly 3000 hours of operation, the reflectivity of the EUV collector mirror is hardly degraded. The availability in system operation was confirmed to reach 99%. We are currently developing key components for higher repetition rate to further increase the brightness. At the conference, we will present the development progress of our EUV light source system.

Presenting Author

Fumio Iwamoto is a Manager in the Research & Development Division, Advanced Light Source Development Department at Gigaphoton, where he has been working on EUV light source development since 2012. Prior to joining Gigaphoton, he worked at Panasonic from 1995 as a lithography process engineer.

S63

Status Update of EUV light Source Development for Inspection Tools (Invited Presentation)

Keitaro Hayashida, Shinji Tanaka, Masaki Koichi, Masayasu Nishizawa

Lasertec Corporation, 2-10-1 Shin-Yokohama, Kohoku-ku, Yokohama, 222-8552, Japan

In 2023, Lasertec released URASHIMA, a high-brightness EUV light source. URASHIMA has been developed and optimized for ACTIS, an actinic patterned mask inspection (APMI) tool capable of detecting all types of printable defects on EUV masks with high sensitivity and high throughput. ACTIS systems with URASHIMA have been delivered to Lasertec's customers and used at both fabs and mask shops in leading-edge semiconductor device production using EUV lithography.

There are several characteristics of an EUV light source required for APMI. The first is a suitable illumination profile. The light intensity must be high enough to achieve a sufficient signal-to-noise ratio, while the illumination must be uniform and only in the field of view (FOV) region to prevent an excessive heat load on pellicles. Another is debris mitigation. For an EUV light source to operate for a long time, it must have an appropriate mitigation system to prevent the optics from being contaminated. Our EUV light source achieves these requirements with a high degree of reliability by using technologies such as rotating crucibles and gas-based debris mitigation [1]. In this presentation, we will give an update on the progress of the EUV light source development.

[1] Nishizawa et al., "Development of a laser-induced plasma EUV light source suitable for inspection tools", 2023 Source Workshop, Aachen, October 2023

Presenting Author

Keitaro Hayashida has been a member of the EUV light source development project at Lasertec since 2019. He completed his master's degree at the University of Tokyo, Department of Applied Physics, Graduate School of Engineering in 2015. From 2015 to 2019, he worked at Mitsubishi UFJ Research and Consulting and then joined Lasertec in 2019.

S64

XUV Light Sources for Semiconductor Metrology (Invited Presentation)

Peter Smorenburg

ASML

With the breakthrough of EUV lithography, the spatial scale in semiconductor manufacturing has decreased to well below the resolution limits of traditional optical metrology tools. This is why XUV light sources become more and more relevant for novel at-resolution metrology concepts, including lithography mask inspection, device metrology, and various applications in lithography research. ASML studies Soft x-ray (SXR) scatterometry using 10-20 nm wavelength light as a promising next-generation metrology technique for 3D profile metrology and overlay (OVL) applications. This wavelength regime offers unique benefits: (1) Short wavelengths allow for high-resolution measurements at device pitches; (2) Primarily single scattering yields low correlation between parameters and aids physical interpretation of signals; (3) SXR provides 3D capability, with stack heights up to 400 nm supported and high depth resolution due to the broadband source and sensor. We demonstrate SXR for profile metrology of gate-all-around devices, which is the primary upcoming transistor architecture. We furthermore demonstrate sensitivity in overlay measurements directly on device-pitch structures in the presence of an underlying patterned nuisance layer.

Presenting Author

S65

A Compact Laser-driven Short-wavelength Radiation Source (Invited Presentation)

Yusuke Teramoto[1], Paolina Noll[1], Guido Mertens[1], Ralf Kops[1], Margarete Kops[1], Wilko van Nunspeet[1], Marcel Schneider[1], Johannes Ebert[2], Jochen Vieker[2], Klaus Bergmann[2]

[1] Ushio Germany GmbH, Steinbachstrasse 15, 52074 Aachen, GERMANY
[2] Fraunhofer ILT, Steinbachstrasse 15, 52074 Aachen, GERMANY

Short-wavelength radiation sources, such as EUV sources, are used in various fields, especially in the semiconductor industry. The applications are broad and emerging as the semiconductor manufacturing technologies are evolving. Ushio, in collaboration with Fraunhofer ILT, has developed the laser-assisted discharge-produced plasma source (LDP source). The LDP source is used for mask inspection and sample exposure applications. We are also developing a compact laser-produced plasma source (LPP source) for applications that utilize a small emission volume, such as metrology applications. In its small form factor, the source employs a liquid metal-coated rotating disc target to generate EUV light by irradiating it with a focused pulse laser. Recently, we started contributing to the research project "XProLas" [1]. The project is supported by Germany's Federal Ministry of Education and Research (BMBF) to realize a high-brightness X-ray radiation source utilizing a high-intensity laser with industrial and academic partners. In this presentation, we will present the characteristics of the compact LPP source, such as laser intensity and frequency responses, emission profile and spectrum, and the early result of the XProLas experiment.

[1] XProLas - Anwendung von lasergetriebenen Röntgenquellen in Produktionsüberwachung und Analytik: Work supported by the Federal Ministry of Education and Research (BMBF), Germany.

Presenting Author

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

S71

Ultra-compact Inline Transmission-grating Spectrograph for EUV Wavelengths (Invited Presentation)

Sascha Brose[1,2], Serhiy Danylyuk[2], Ismael Gisch[1], Lars Lohmann[1], Annika Bonhoff[1], and Carlo Holly[1,2]

[1]RWTH Aachen University TOS - Chair for Technology of Optical Systems, Steinbachstr. 15, 52074 Aachen, Germany;
[2]Fraunhofer ILT - Institute for Laser Technology, Steinbachstr. 15, 52074 Aachen, Germany

In this contribution the design aspects and implementation of the transmission grating spectrograph (TGS) for spectral characterization and monitoring tasks at EUV wavelengths is presented. The overall dimensions of the EUV-TGS have been further minimized to allow for simple integration in existing beamlines and setups while maintaining sub-Angstrom spectral resolution. The main module (dimensions of 25 x 25 x 40 mm^3) of the realized EUV-TGS consists of a spectral and a spatial filter and a high-resolution phase-shifting transmission grating with a periodicity of 80 nm. For spectral monitoring, a CCD camera is positioned in proximity to the main module. If the spectrograph is positioned out of the beam path, spot profiling and general beam adjustment steps can still be carried out. The measurement performance of the EUV-TGS is presented, demonstrating that this ultra-compact spectrograph can be easily introduced into EUV setups that will benefit from an inline diagnostic option. The current design has been further optimized and will be combined with an in-vacuum CCD camera to extend the use-cases of the EUV-TGS.

Presenting Author

Dr. Sascha Brose received the Ph.D. degree in mechanical engineering in 2019 from RWTH Aachen University and is group manager of the research group “EUV technology” at the Chair for Technology of Optical Systems (TOS) at the RWTH Aachen University. Already since 2009 he is working in the field of extreme ultraviolet (EUV) applications with focus on the conceptual design, functionalization, and operation of EUV tools for high-precision metrology and nanoscale patterning. His research fields include EUV lithography, EUV metrology and material modification by focused EUV radiation. Additionally, he is expert in micro- and nanofabrication processes of optical components especially designed for EUV wavelengths. He has authored and co-authored more than 40 scientific publications mainly in the field of EUV lithography and metrology.

S72

From EBL Gratings to Advanced Photonics for the inspection of Complex Nanostructures

Analía F. Herrero[1,2], V. Truong[1], S. Rehbein[2], F. Siewert[2], F. Scholze[1], V. Soltwisch[1]

[1]*Physikalisch-Technische Bundesanstalt, Abbestr. 2-12 10587 Berlin*
[2] *Helmholtz-Zentrum Berlin, Albert-Einstein Str. 15, 12489 Berlin*

The properties of nanostructured surfaces are determined by their composition, size and shape. The continuously shrinking dimensions of the features and their increasing complexity require non-destructive methods with high throughput that are able to asses complex 3D structures. Measurement techniques based on light-structure interaction allow a fast and non-destructive inspection of structured areas and are already widely used in the infrared, visible and hard X-ray spectral ranges. The German national metrology institute (PTB) is engaged at the storage rings BESSY II and MLS with the development of metrology in the UV to X-ray spectral ranges; the wavelength range from 0.12 nm to 50 nm is covered at different beamlines. PTB’s radiometric capabilities allow accessing fluorescence, scattering and reflected signals in a quantitative and traceable manner. Computational methods are developed for the complete numerical simulation of the measurements, including parameters like beam divergence and energy spread. Those parameters as well as the assessment of optical constants of the materials in the soft X-ray range improve the reconstruction. We also investigate the combination of several methods, e.g. fluorescence and scattering simultaneously, so-called hybrid metrology, to enhance the robustness of the results.

All these methods profit from the significant improvements in brilliance, stability, and coherence within storage rings in the last decades. For VUV-, soft-, and tender-X-ray photon energy ranges, high-quality blazed gratings are essential. However, the manufacturing process constrains their availability and flexibility. Within the framework of LEAPS-INNOV (Open innovation for accelerator-based light sources in Europe, EU´s Horizon 2020, grant agreement no. 101004728) the possibility of producing these gratings using gray-tone electron-beam lithography (EBL) has been studied, showing very good performance.

Here, we give an overview of the existing experimental and computational tools for the characterization of nanostructures, as well as the promising blazed profile gratings for soft X-rays fabricated by EBL.

Presenting Author

Analía F. Herrero has worked on the development of optical elements and metrology methods for synchrotron radiation during the last 12 years. She did her PhD thesis on the characterization of line-edge roughness on periodic nanostructures at the national metrology insitute in Germany, PTB. After a PostDoc at Helmholtz Zentrum Berlin developing optical elements for the EUV and soft X-ray energy region, she is back at PTB, where she develops metrology methods for the characterization of nanostructured surfaces.

S73

EUV-sources for Optics-lifetime and Materials Testing (Invited Presentation)

Lucas Poirier

TNO, Stieltjesweg 1, 2628 CK, Delft, the Netherlands

The development of EUV lithography machines requires extensive testing of optics, parts and materials. TNO has over 20 years of experience with the design, realization and use of EUV test setups and has worked with leading companies in the semiconductor market. The presentation highlights results from our current EUV test infrastructure. We also share preliminary plans for a new EUV setup, including a discussion on source requirements for the application of EUV testing.

EUV Beamline 2 (EBL2) is our main EUV test facility. It was designed and developed at TNO for the study of lifetime of materials including but not limited to EUV optics used in the nanolithography industry. The business model and beamline components are laid out, with special attention to EUV source performance such as EUV power, repetition-rate, stability, and intensity distribution. The environment control capacities (thermal control, gas environment, background pressure quality *etc.*) and metrology tools of the exposure chamber are also presented. We highlight the in-situ x-ray photoelectron spectroscopy (XPS) and the ellipsometer tool, which provide for live inspection of the exposed samples. The variety of compatible samples (including EUV masks) and metrology tools also enable a great flexibility with projects conducted at EBL2.

Presenting Author

Lucas Poirier is a scientist for the EUV beamline 2 (EBL2) at the Semicon Equipment Lifetime department of TNO. His tasks include helping to maintain and to upgrade the beamline and providing scientific support for projects conducted at EBL2. He is also involved in other projects, specifically projects involving plasma metrology of EUV-induced plasma. Lucas finished his PhD at ARCNL in October 2023, where he studied tin ion emission from laser-produced plasmas in the context of EUV sources.

S74

EUV Source Metrology using Transmissive and Diffractive Optics (Invited Presentation)

Muharrem Bayraktar

XUV Optics Group, MESA+ Institute for Nanotechnology,
University of Twente, Drienerlolaan 5, 7522 NB Enschede, The Netherlands

Latest generation of extreme ultraviolet (EUV) lithography and metrology light sources require versatile metrology tools to characterize their energy, spectral and spatial properties. Besides the strong in-band emission, these plasmas emit out-of-band radiation in a broad wavelength range spanning from soft x-rays to visible wavelengths from different spatial positions of the plasma. A broadband spectral and spatial metrology of EUV plasma sources is crucial not only from the fundamental science perspective to understand the plasma emission characteristics, but also from the industrial perspective for online monitoring to optimize sources for increased in-band and reduced out-of-band emission.

In this presentation a survey of metrology tools for EUV light sources is presented. The presentation first covers methods for absolutely calibrated in-band metrology using narrowband reflective and anomalous transmission-based tunable filtered photodiodes. In the second part, broadband spectral characterization of various EUV sources using free-standing transmission gratings is presented. In the last part, a novel imaging spectroscopy tool that is combining transmission gratings with diffractive zone plates is presented.

Presenting Author

Muharrem Bayraktar received his B.S. (2007) from Bilkent University in electrical and electronics engineering, his M.Sc. (2010) from Sabanci University in electronics engineering, and his Ph.D. (2015) from University of Twente in applied physics. He is an assistant professor in XUV Optics Group at the MESA+ Institute for Nanotechnology, University of Twente. His present research interests include piezo-/ferroelectric thin films for adaptive short wavelength optics including mirrors and wafer tables, and metrology of EUV sources with novel spectroscopy techniques.

S75

EUV Reflectometry and Non-Destructive Nanoscale Sub-Surface Imaging with HHG Sources (Invited Presentation)

Martin Wünsche[1,2,3], Silvio Fuchs[1,2,3,4], Johann Jakob Abel[2,3], Julius Reinhard[2,3], Gerhard G. Paulus[2,3]

1 Indigo Optical Systems GmbH, Moritz-von-Rohr-Str. 1a, 07745 Jena, Germany
2 Institute of Optics and Quantum Electronics, Max-Wien-Platz 1, 07743 Jena, Germany
3 Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena, Germany
4 Laserinstitut Hochschule Mittweida, Technikumplatz 17, 09648 Mittweida, Germany

The 2023 Nobel Prize in Physics has brought significant recognition to high-harmonic generation (HHG) and its unique capabilities. HHG provides exceptional flexibility with its broad spectral range, spatial coherence, and ultrashort pulse duration, making it ideal for advanced metrology. For over 15 years, we have been developing and refining non-destructive, high-resolution imaging techniques that leverage the power of HHG.
We present an innovative imaging method using broadband extreme ultraviolet (EUV) light in reflection. This technique enables three-dimensional sub-surface imaging with nanometer-scale resolution and utilizes Fourier-domain analysis to minimize the need for complex optics. Completely non-destructive, it provides detailed structural information while also characterizing material composition and broadband EUV reflectivity, crucial for analyzing nano-thin EUV layers. Additionally, it can easily detect small encapsulations, such as monolayers. Our table-top broadband HHG source allows for the non-destructive examination of samples across a wide spectral range (from below 12 nm to 40 nm), making it particularly suitable for the analysis of lithography samples and layered structures.

Presenting Author

Martin Wünsche received his PhD in 2020 from the University of Jena, Germany. During his doctoral research, he developed an HHG-driven EUV setup, encompassing source development, diagnostics, and reconstruction algorithms for various HHG-based EUV metrology applications. He is the co-founder and CEO of Indigo Optical Systems GmbH, a spin-off from the University of Jena, specializing in the development of high-resolution EUV spectrometers, monochromators, beamlines, and advancing innovative EUV metrology solutions.

S76

Extreme-ultraviolet High-intensity Exposure Setup for Small-spot In-band Exposures

Linus Nagel[1], Ismael Gisch[1], Adelind Elschani[1], Sascha Brose[1,2], Annika Bonhoff[1], and Carlo Holly[1,2]

[1]RWTH Aachen University TOS - Chair for Technology of Optical Systems, Steinbachstr. 15, 52074 Aachen, Germany;
[2]Fraunhofer ILT - Institute for Laser Technology, Steinbachstr. 15, 52074 Aachen, Germany

The extreme ultraviolet high intensity exposure (EUV-HIEX) setup is a compact tool for irradiation of samples with high EUV doses designed to achieve maximum intensity within a small spot size in the sample plane. Applications can be found in the field of accelerated lifetime studies where the EUV-material interaction is investigated. Further applications are EUV induced outgassing studies and material modifications within adjustable gas atmospheres covering industrial to fundamental research tasks. For the realization of the experimental setup broadband EUV radiation is emitted by a discharge-produced plasma EUV source. The radiation is deflected using a multilayer (ML) mirror optimized for an incidence angle of 45 degrees. The initial broadband emission is narrowed down by the ML mirror to in-band EUV at a main wavelength of 13.5 nm. By the implementation of a two shell Wolter collector, using external total reflection under grazing incidence angle, the emitted radiation is focused into sample plane, offering tunability to from a small-spot (≈ 80 µm FWHM) or a top-hat distribution (≈ 200 µm FWHM). In addition, a thin film system serves as an out-of-band filter with a high transmission for wavelengths between 5 nm and 20 nm. The exposure spectrum in sample plane is experimentally characterized regarding its main wavelength and spectral bandwidth. A supporting ray-tracing simulation confirms the high intensity level, with average peak intensities of 1 W/mm² considering the full bandwidth from 5 to 19 nm, whereas the in-band peak intensity is exceeding 100 mW/mm² for 13.5 nm with ± 1% bandwidth. Intensity levels, high spectral purity and the integrated sample handling system allow for in-band lifetime tests for industrially relevant EUV components.

Presenting Author

Linus Nagel graduated 2022 in mechanical engineering at RWTH Aachen University within the field of EUV technology. Subsequently to his master's thesis: "Design of a compact laboratory setup for photoelectron spectroscopy using EUV radiation" he works on his Ph.D. thesis at the Chair for Technology of Optical Systems (TOS) since early 2023. His main topics are EUV photoelectron spectroscopy as well as EUV high intensity irradiations.

S77

How Can We Achieve At-resolution Metrology in Optical Microscopy? (Invited Presentation)

Peter M. Kraus[1,2]

1) *Advanced Research Center for Nanolithography (ARCNL), Science Park 106, 1098 XG Amsterdam, The Netherlands, kraus@arcnl.nl*
2) *Department of Physics and Astronomy, and LaserLaB, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*

Much of the current wafer metrology measures on targets that have substantially larger pitches and critical dimensions than the actual device. Electron-beam techniques can solve the resolution limit, but are generally invasive and limited in throughput. Soft-X-ray metrology is an adequate tool for at-resolution metrology, but comes with complex instrumentation.

Here we propose a novel route that aims to bring super-resolution techniques to the semiconductor manufacturing process. Existing super-resolution microscopy requires fluorescent labeling, which is not an option for the semiconductor industry. We therefore have developed a new approach, that makes use of light-field control of nonlinear optical processes – in particular of high-harmonic generation (HHG) [1] from the semiconductor nanostructure of interest itself – to achieve super resolution.

In this talk, I will present our vision to use this light-field control of HHG for super-resolution nanoscale imaging by HHG. In particular, I will present three key experiments on our roadmap towards this goal. On the nanoscale, we controlled HHG via engineering the surface topography of solids, which in turn demonstrates how solid HHG can be used for metrology on surfaces and tailored as a light source [2-4].
On the femtosecond time scale, we investigated how we can deactivate HHG efficiently and create an all-optical light switch [6]. While the first measurements [2] showed nanoscale sensitivity, the second set of experiments [5,6] demonstrated that photoexcitation can be used to control light emission via solid HHG. Combining both efforts, I will show first results how ultrafast control of solid HHG enables HArmonic DEactivation microScopy (HADES) - a label-free super-resolution microscopy below the diffraction limit of light [7].

Thinking ahead, the development of these techniques may enable resolution on the nanometer (and in principle even femto- to attosecond scale) fitted into a regular optical microscope operating in the visible and ultraviolet range. This feat may enable at-resolution semiconductor metrology in the future.

[1] P. v. Essen, Z. Nie, B. de Keijzer, P.M. Kraus, arXiv:2402.15375, ACS Photonics, accepted (2024).
[2] S.D.C. Roscam Abbing, R. Kolkowski, Z.-Y. Zhang, F. Campi, L. Loetgering, A.F. Koenderink, P.M. Kraus, Physical Review Letters 128, 223902 (2022).
[3] P. M. Kraus et al., US Patent App. 18/038,590 (2024).
[4] P. M. Kraus et al., US Patent App. 18/253,734 (2024).
[5] Z. Nie et al., Peter M. Kraus, Physical Review Letters, 131, 243201 (2023).

[6] M. v.d. Geest, J.J. de Boer, K. Murzyn, P. Juergens, B. Ehrler, P.M. Kraus, Journal of Phys. Chem. Lett., 14, 10810 (2023).
[7] K. Murzyn, M.v.d. Geest, L. Guery, Z. Nie, P.v. Essen, S. Witte, P.M. Kraus, arXiv:2403.06617, submitted (2024).

Presenting Author

S81

Predicting the Chemical Stability of Thin-film Coatings in Hydrogen for EUV Applications

Abdul Rehman, Robbert W.E. van de Kruijs, Wesley T.E. van den Beld, Jacobus M. Sturm, Marcelo Ackermann

Industrial Focus Group XUV Optics, MESA+ Institute for Nanotechnology, University of Twente, Drienerlolaan 5, 7522NB Enschede, the Netherlands

Prediction of the chemical stability of materials in EUV-induced H-plasma is crucial for the development of many components in current day EUV-scanners. Materials exposed to EUV-induced H-plasma undergo degradation (etching/reduction), leading to a decline in their functionality. One of the key processes in the complex interaction of EUV-induced H-plasma with materials is the interaction of hydrogen radicals (H*) with the surfaces, as H* is believed to be the primary contributor to materials' degradation.

TMN/O are candidates for various applications in EUV-scanners due to their exceptional physical properties and effective H permeation-barrier performance. However, they tend to partially reduce (de-nitridize/de-oxidize) in H*. Our findings show that the N/O-reduction reaction effectively stops when the work function drops below 4.3±0.4 eV [1]. This value aligns with literature [2], where for ≈ 4.3 eV it was shown that H^+ and H^- have equal formation energies in semiconductors/insulators. We here propose that the reduction of TMN/O in H* depends on H* binding to TM-atoms (H^+) or N/O-atoms (H^-) and is therefore governed by the TMN/O's work function. When below 4.3±0.4 eV, H* preferably binds to TM-atoms, rather than N/O-atoms, making TMN/O non-reducible.

This work shows that the work function is one of the key parameters for predicting/tailoring the chemical stability of materials in EUV-induced H-plasma.

[1] Rehman, Abdul, et al. "Work Function Dependent Reduction of Transition Metal Nitrides (TMNs) in Hydrogen Environments." arXiv preprint arXiv:2403.11765 (2024).
[2] Van de Walle, Chris G., and Jörg Neugebauer. "Universal alignment of hydrogen levels in semiconductors, insulators and solutions." *Nature* 423.6940 (2003): 626-628.

Presenting Author

Abdul Rehman is a Ph.D. candidate in the XUV Optics group at the University of Twente. His research focuses on the interaction of reactive hydrogen species with material surfaces, aiming to identifying the key parameters that govern these interactions.

S82

Investigating EUV Degradation with In-situ EUV Transmission Measurements

Duncan Ramsamoedj, Wesley van den Beld, Marcelo Ackermann

Industrial Focus Group XUV Optics, MESA+ Institute for Nanotechnology, University of Twente, Drienerlolaan 5, 7522NB Enschede, the Netherlands

The degradation resistance of materials in EUV and H_2 plasma is critical for EUV lithography processes and equipment. Therefore, our study investigates in-situ time-resolved EUV- and plasma-driven degradation of transition metal oxides (TMO) to understand EUV degradation. The hypothesized mechanism is based on Auger decay due to photoelectrons. Thus, we predict that the electronic structure of a TMO determines its EUV stability.

For a first exposure run, two TMOs were chosen according to their hypothesized stability. The stability was monitored with in-situ EUV transmission (EUVT) measurements. The stable material had no significant change in EUVT, while the EUVT of the unstable material decreased, which is in line with the hypothesis. Ex-situ EUV reflectivity and X-ray reflectivity show an increase in layer thickness, indicating oxidation, for which a more detailed model is proposed. In addition, the EUV degradation in a hydrogen environment was investigated, where the effect of hydrogen was not significant, confirming out hypothesis that materials stable in "offline" hydrogen exposures are also stable in EUV plasma.

These findings will increase the understanding of EUV and H_2 plasma stability of different materials in EUV lithography processes.

Presenting Author

Duncan Ramsamoedj, a first year PhD candidate at the XUV optics group of the University of Twente in the Netherlands. He has a background in physical chemistry and his project is to create a detailed understanding on material/ surface degradation in an EUV-driven plasma environment.

Short-wavelength EUV source by a Continuous Liquid Bismuth Jet

Tatsuya Soramoto,[1] Ayaka Ogiwara,[1] Hiroki Morita,[1] Shinichi Namba,[2] and Takeshi Higashiguchi[1]

[1]Department of Electrical and Electronic Engineering, Faculty of Engineering, Utsunomiya University, 7-1-2, Yoto, Utsunomiya, Tochigi 321-8585, Japan
[2]Department of Advanced Science and Engineering, Hiroshima University, 1-4-1, Kagamiyama, Higashihiroshima, Hiroshima 739-8527, Japan

Extreme ultraviolet (EUV) lithography has been the subject of intense research that has successfully developed exposure tools using a laser-produced tin (Sn) plasma source operating at a peak wavelength of 13.5 nm. As semiconductor chips become more high-performance, EUV lithography requires a shorter wavelength light source. Water-window (WW) soft x-ray (SXR) wavelength at 2.3 – 4.4 nm is considered the next-generation short-wavelength EUV source as a "Blue-X" project [1]. In addition to low-*Z* elements such as C and N, high-*Z* elements such as Mo, Au, and Bi are considered targets for WW-SXR sources. Currently, SXR sources using high-*Z* elements are mainly operated as single-shot operations with solid targets, and no report demonstrates high repetition and continuous operation with a liquid high-*Z* target. Therefore, we focused on the fact that Bi in the target candidates has a relatively low melting point and can be easily liquefied, and we developed the liquid Bi target. In this presentation, we will show the high repetition and long-time operation of the WW-SXR source using continuous liquid Bi targets and their SXR emission characteristics.

[1] V. Bakshi, *EUV Roadmap Needs Extension*, EE Times (2018); https://www.eetimes.com/euv-roadmap-needs-extension/

Presenting Author

Tatsuya Soramoto is a graduate student in engineering at the Utsunomiya University. His research activities have focused on developing regenerative liquid targets for EUV and SXR light sources and measuring the characteristics of light sources using such targets.

S84

Enhancement of the EUV Conversion-efficiency using Multiple-Solid-state-laser Pulses

Tsukasa Sugiura,[1] Hayato Yazawa,[1] Hiroki Morita,[1] Atsushi Sunahara,[2] Shinichi Namba,[3] and Takeshi Higashiguchi[1]

[1]Department of Electrical and Electronic Engineering, Faculty of Engineering, Utsunomiya University, 7-1-2, Yoto, Utsunomiya, Tochigi 321-8585, Japan
[2]Center for Materials Under Extreme Environment (CMUXE), School of Nuclear Engineering, Purdue University, West Lafayette, Indiana 47907, USA
[3]Department of Advanced Science and Engineering, Hiroshima University, 1-4-1, Kagamiyama, Higashihiroshima, Hiroshima 739-8527, Japan

We demonstrated the EUV conversion efficiency (CE) enhancement using a multiple-solid-state-laser pulse. The EUV CE was measured as the number of laser pulses ranged from one to five with an EUV source size of approximately 100 mm, a laser intensity of 2×10^{11} W/cm^2, and a total laser pulse energy of 500 mJ. The maximum EUV CE of 3.8% was achieved with oblique two-laser pulse irradiation at $\pm$ 30°, about twice the 1.7% with vertical one-laser pulse irradiation. Although the EUV source size was 200 mm, the EUV CE of 4.7% was achieved with oblique two-laser pulse irradiation of $\pm$ 60°, the highest value ever reported for laser-produced solid tin (Sn) plasma. Therefore, the EUV CE could be enhanced using a multiple-solid-state-laser pulse [1]. This result suggests that for high-power EUV sources, multiple-solid-state-laser pulse irradiation at high repetition rates could be the next technology to replace the current CO_2 laser in future technology nodes.

[1] T. Sugiura, H. Yazawa, H. Morita, K. Sakaue, D. Nakamura, E. J. Takahashi, A. Sunahara, G. O'Sullivan, S. Namba, and T. Higashiguchi, Appl. Phys. Lett **125**, 034103 (2024).

Presenting Author

Tsukasa Sugiura is a graduate student in engineering at Utsunomiya University. His research has focused on observing the UTA spectra and fast ions from the laser-produced plasma EUV sources.

S85

Observation of Surface Modulation on Free-Flying Liquid Metal Sheets

H.K. Schubert[1,2], D.J. Engels[1,2], M. Kharbedia[1], and O.O. Versolato[1,2]

1: Advanced Research Center for Nanolithography (ARCNL), Science Park 106, 1098 XG Amsterdam, The Netherlands
2: LaserLab, Department of Physics and Astronomy, Vrije Universiteit Amsterdam, De Boelelaan 1105, 1081 HV Amsterdam, The Netherlands

We study the interaction of ns laser pulses with µm-sized liquid tin droplets, resulting in an expanding sheet with non-steady time evolution. During the liquid tin sheet evolution, we observe that an inner sheet part reflects incoming shadowgraphy light with radially periodically changing contrast on both sides of the sheet. From this we learn that the inner sheet part must have height undulations in form of ripples. Furthermore, we learn that these concentric contrast rings propagate radially outwards with time and appear to be phase-correlated for front and back view, indicating an instability to on both sides from the same source. Our in-house developed raytracer model (RT) explains the reflection pattern from the metallic sheet and suggests a very low ratio between wave amplitude and wavelength. We experimentally confirm the low amplitude of the capillary waves by using a vaporization pulse (VP). Given the sheet thickness h and dominant wavelength λ, wave dynamics fall into the shallow water limit with $h << \lambda$. However, matching reflection and transmission shadowgraphs does not conclusively determine the phase relationship of the waves, indicating that they could be either in-phase or out-of-phase, corresponding to antisymmetric or dilational (symmetric) waves in the linear regime. Finally, the ripple phase dynamics appear highly dependent on laser intensity, with complex wave-breaking phenomena observed.

Presenting Author

Karl achieved his B.Sc. at the University of Leipzig from 2015 to 2019, specializing in ion sputtering on thin films. He further obtained a M.Sc. at FSU Jena from 2019 to 2021, focusing on ultra-short tunable sources. Since 2021, Karl is a PhD at ARCNL Amsterdam, where his research centers around target shaping of liquid tin droplets that are used in state-of-the-art EUV-nanolithography machines.

S87

2024 Source Workshop Poster Presentation (Tentative Title)

TBA

Energetiq

Presenting Author

S88

High Harmonic Generation with a Compact Amplification-free Thin-disk Laser-oscillator System

Moinuddin Kadiwala, Yasmin Kopp, Semyon Goncharov, Nazar Kovalenko, and Oleg Pronin

Helmut Schmidt University, Holstenhofweg 85, 22043 Hamburg, Germany

Many applications in fundamental and applied research; for example, high-resolution laser spectroscopy of Th-229 and XUV metrology require coherent sources far beyond the visible or even the XUV and soft X-ray spectral regions. It is possible to reach these spectral ranges via high harmonic generation. In this work, we will report on the generation of the 7^{th} harmonic, 150 nm, of Yb-based thin-disk laser. In-house developed oscillator delivers 120 fs pulses at a rep. rate of 14 MHz containing pulse energy of roughly 13 µJ resulting in an average power of 180 W and, corresponding to 100 MW [1,2]. The output of the TDL is compressed down to 40 fs using a multipass cell. The compressed beam was focused into a gas jet (Argon and Krypton) resulting in a peak intensity of 9 x 10^{13} W/cm^2. The 7^{th} harmonic signal was recorded using an XUV photodiode. Preliminary results show a conversion efficiency on the order of 10^{-6}. In the near future, we plan to install a toroidal diffraction grating along with a CCD camera to characterize and optimize the full high harmonic spectrum aiming for reaching the wavelength range of 13 nm and driving the high harmonics with <10 fs pulses. These results are the first steps towards realizing high-power, and high-repetition rate XUV frequency combs for applications in high-precision XUV frequency-comb spectroscopy and XUV metrology.

1 S. Goncharov, K. Fritsch, and O. Pronin, "110 MW thin-disk oscillator," Opt. Express 31, 25970-25977 (2023)
2 Semyon. Goncharov, K. Fritsch, and O. Pronin, "Amplification-free GW-level, 150 W, 14 MHz, and 8 fs thin-disk laser based on compression in multipass cells," Opt. Lett. 49, 2717-2720 (2024)

Presenting Author

Moinuddin Kadiwala is a PhD student at the Helmut-Schmidt University. He received his master's degree in physics from University of Hamburg, majoring in the subject of lasers and photonics. Since December 2023, he is working at the Chair for Laser Technology and Spectroscopy. His research topics include the development of a table-top VUV/XUV frequency comb for the application of high resolution spectroscopy.

S89

Numerical Study of Laser-Produced Plasma Light Source on Improving Conversion Efficiency by Three Pulse Scheme

Chun-Tse Wu[1], Yao-Li Liu[2], Po-Yen Lai[1], Chia-Hsiang Chen[3], Chun-Lin Chang[3], and Shih-Hung Chen[1]

[1]Physics, National Central University, Taoyuan, Taiwan
[2]Institute of Space and Plasma Sciences, National Cheng Kung University, Tainan, Taiwan
[3]Taiwan Semiconductor Manufacturing Company, Hsinchu, Taiwan

Laser-produced tin plasma serves as 13.5 nm light source for cutting-edge lithography, enabling continued transistor miniaturization and supporting Moore's law. Previous studies [1] have extensively explored methods to optimize the conversion efficiency (CE). Among the numerous methods, the double-pulse scheme has emerged as a widely recognized approach [2]. In this scheme, a pre-pulse (PP) increases the target's cross-sectional area while reducing its density, allowing the main pulse (MP) to be absorbed more uniformly. As a result, more tin ions are heated, emitting extreme ultraviolet (EUV) light. In present research, we investigate the three-pulse scheme to further optimize CE. An additional laser pulse is introduced between PP and MP. This pulse heats the target before the MP is injected, adjusting the target's density and temperature. When the plasma density is low and plasma temperature is high, the laser absorption is weak. Therefore, the laser energy can penetrate deeper into the target, increasing the number of EUV-emitting ions. Our investigation is conducted using our one-dimensional simulation framework [3] that has been benchmarked against experimental data [4] and shows good agreement. The results indicate that adding a Gaussian pulse between the PP and MP can improve CE by 13% to 18%.

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Presenting Author

Chun-Tse Wu is a PhD student at National Central University, specializing in the simulation of laser-produced plasma EUV light sources. My research focuses on optimizing conversion efficiency through the adjustment of laser pulse parameters. I have actively participated in the scientific community, including attendance at the CLEO conference, a leading international event that showcases cutting-edge research and developments in lasers and photonics.

S90

Broadband Reflective Spectrometer for High-resolution Spectral Characterization of Radiation Sources

Ismael Gisch[1], Sophia Schröder[1], Sven Glabisch[1], Sascha Brose[1,2], Serhiy Danylyuk[2], Annika Bonhoff[1], Carlo Holly[1,2]

[1] RWTH Aachen University TOS - Chair for Technology of Optical Systems, Steinbachstr. 15, 52074 Aachen, Germany
[2] Fraunhofer ILT - Institute for Laser Technology, Steinbachstr. 15, 52074 Aachen, Germany

The development of compact radiation sources has enabled a multitude of lab-size applications, especially in the field of metrology [1]. A broadband spectral characterization of the source emission is of utmost importance for the investigation of photon-induced processes and metrology [2]. In this study, the authors present a unique setup and corresponding measurement results for the high-resolution broadband spectral characterization of radiation sources covering the extensive wavelength range from 5 nm to 1000 nm. The achievable resolution is 0.02 nm in the short wavelength range and the resolving power (l/Dl) exceeds 600 for the full range. For the vacuum wavelength range (5 nm to 200 nm) the setup employs several flat-field diffraction gratings with varying line density as dispersive elements. The wavelength range above 200 nm is measured with two Czerny-Turner spectrometers. The main components of the spectrometer have undergone rigorous characterization at the Physikalisch-Technische Bundesanstalt (PTB, Berlin). Higher diffraction orders are filtered out by a selection of spectral thin film filters. The resulting spectra from measurements are combined to obtain the full spectrum without any higher diffraction order contributions. The contribution will cover the overall design, the wavelength calibration and the relative as well as the absolute intensity calibration of the measured spectra.

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[2] Z. Bouza, J. Byers, J. Scheers, R. Schupp, Y. Mostafa, L. Behnke, Z. Mazzotta, J. Sheil, W.M.G. Ubachs, R. Hoekstra, M. Bayraktar and O.O. Versolato, (2021), AIP Advances 11, (12), 125003: 1-9

Presenting Author

Ismael Gisch is a Ph.D. student at RWTH Aachen University. He received his bachelor's and master's degrees in physics, majoring in the subject of solid-state physics. Since 2022, he has been working in the EUV technology group at the Chair for Technology of Optical Systems. His research topics include broadband spectroscopy of radiation sources along with the corresponding data analysis and plasma physics.

S91

LEUS: A Novel LPP EUV Light Source with Fast-Rotating Lithium Target and Unique Spectral Brightness

Alexander Tovstopyat*, Mikhail Krivokorytov, Vladimir Gubarev, Nazar Vorona, Sergey Zyryanov, Alexey Zotovich, Alexander Vinokhodov, Vladimir Ivanov, Vladimir Krivtsun, Alexander Lash, Vyacheslav Medvedev, Denis Glushkov, Samir Ellwi, Eugene Gorsky and Konstantin Koshelev

ISTEQ Group, Eindhoven, The Netherlands

Diffractive optical systems based on zone plates are a well-known technique for achieving high spatial resolution imaging. Zero-aberration, diffraction-limited illumination points offer high detection sensitivity, making these systems ideal for actinic EUV inspection and metrology. Typically, zone plates require monochromatic light. While synchrotron radiation is ideal for such systems, it is often unavailable to small-scale laboratories. With advances in ultrafast laser technology, EUV light sources based on high-order harmonic generation (HHG) have become widespread, though they often struggle to provide sufficient photon flux to meet industrial needs. Classical xenon/tin-based LPP and discharge EUV sources require preliminary monochromatization of the radiation, leading to significant EUV losses. Lithium plasma has long been considered a potential EUV source due to its narrow spectral peak at 13.5 nm and extremely high spectral brightness; however, this approach has faced numerous technological challenges until recently.

This report first introduces a novel LEUS-type EUV LPP light source, which employs a fast-rotating target and liquid lithium-based fuel to generate plasma. The serial LEUS instrument with 100 W laser radiates EUV emission in a single spectral line at 13.5 nm with $\lambda/\delta\lambda$ >1000, resulting in a spectral brightness exceeding 1000 W/nm·mm^2·sr. With a laser focal spot diameter of less than 60 μm on the lithium surface, the conversion efficiency reached 0.6%, and the EUV flux (within a collection angle of 0.05 sr after the debris mitigation system) was recorded at 2.3 mW. Using more powerful lasers gives a natural potential for future enhancements of the instrument characteristics. We expect that the LEUS light sources will be widely used in various metrology systems in lithography and related industrial fields.

[1] Mikhail Krivokorytov et al. "EUV LPP light source based on fast rotating target. Target material variants and way to increase spectral brightness." 2023 Source Workshop Abstract Book, Aachen, Germany, p. 34(S71).

Presenting Author

Alexander Tovstopyat is the Head of Production at ISTEQ EUV, focusing on the production and development of EUV light sources. Alexander received his PhD in physics by studying organic microelectronics at Graz University of Technology. After several years of leading a group working on cleaning and modification of the properties of glass-ceramic surfaces by RF plasma treatment at JSC Research Institute "Polus", he took the position of Associated Professor at Wuhan University in 2019. In 2023 Alexander joined the ISTEQ EUV team.

S92

EUV and Soft X-ray Optical Evaluation System Development in TOYAMA

Akira Miyake

TOYAMA CO., LTD., 3816-1 Kishi, Yamakita-machi, Ashigarakami-gun Kanagawa, 258-0112, JAPAN

Toyama has been developing and manufacturing ultra-precision optical and vacuum systems such as X-ray beamline optics, spectrometers, and surface analysis equipment for synchrotron radiation facilities for many years. Applying the technology and experience, we are developing EUV and soft X-ray optical evaluation systems in cooperation with EUV or X-ray source manufacturers and EUV-related customers. In the next few years, we plan to develop the following optical systems.

・EUV reflectivity and transmittance evaluation equipment

・EUV source evaluation equipment

・EUV light irradiation equipment for various material samples

・EUV/X-ray microscope

In developing these systems, EUV or X-ray optics is designed to achieve required beam size, spectrum purity, and photon flux on the sample considering the characteristics of the light source to be used. To realize the designed optical system, precision mechanical system to mount and adjust the optical elements, vacuum system, are designed and software to automatically control the entire system are developed.

In this presentation, overview about the optical systems under development are provided.

The specifications of the light source required for the system are also discussed.

Presenting Author

Akira Miyake is a chief engineer at TOYAMA in charge of optical design of X-ray optical systems. After studying X-ray astronomy at Osaka University, he joined Canon Inc. in 1987 and was involved in the X-ray and EUV lithography system development. Since 2015, he has also been involved in the astronomical telescopes and satellite optical systems. From 2020 to 2023, he was involved in the development of measurement technologies for X-ray mirrors and X-ray optical systems at JTEC Corporation.

EUV

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