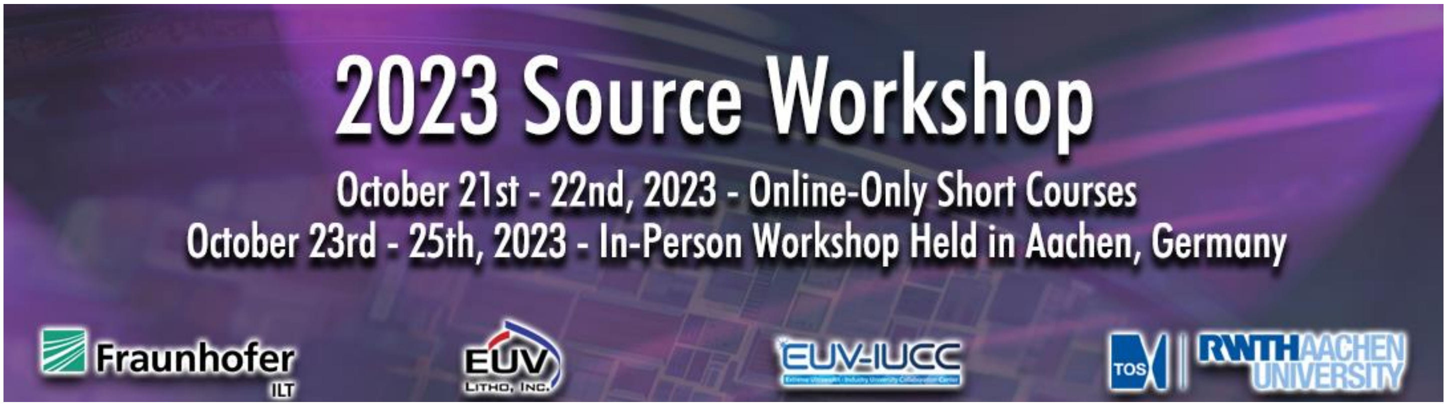


Workshop Abstracts

EUV Litho, Inc.

Organized By:

Vivek Bakshi (EUV Litho, Inc), Chair

Sascha Brose (RWTH / ILT), Co-Chair

Jochen Vieker (Fraunhofer ILT), Co-Chair

Contents

2023 Source Workshop Abstracts

Listed by Abstract Numbers


Thank You To Our Executive Sponsors!
ISTEQ EUV


Thank You To Our Gold Sponsors!
EDGEWAVE
ENERGETIQ
A HAMAMATSU Company
TAU
USHIO

Trends and Perspectives of Advanced Photon Source Development (Keynote)

Constantin Häfner[1,2], Carlo Holly[1,3], Johannes Weitenberg[1,2], Martin Adams[1], Klaus Bergmann[1], Sascha Brose[1,3], Christian Hinke[1,2], Hans-Dieter Hoffmann[1], Peter Russbüldt[1], Jochen Stollenwerk[1,3], Jochen Vieker[1], Rolf Wester[1]

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

Intense photon sources with various combinations of power, brilliance, wavelength, and pulse parameters are of paramount importance in a broad spectrum of scientific research, production, metrology, and life science applications. Fraunhofer ILT plays a vital role in developing incoherent plasma-based extreme ultraviolet (EUV) sources and coherent laser sources that cover a wide range of wavelengths from EUV to mid-infrared (MIR). These sources are essential for both industrial and scientific applications, including those that require systems suitable for use in air-borne or spaceborne environments. Attaining an advanced level of technology maturation is imperative for the efficient deployment of these systems while ensuring their robustness, maintainability, and reliability. The development process necessitates vast expertise in laser physics, optical design, optical component design, source simulation, precision soldering, and system integration. For airborne or spaceborne laser sources alignment is performed in liquid solder without screws allowing tolerances in the range below 10 µrad under vibration load and temperature variations. This glue free packaging also avoids outgassing. Furthermore, proficiency in testing (including vacuum testing, vibration testing, and thermal cycling), as well as experience in system integration and deployment, is crucial. These competencies collectively enable the construction of dependable systems with accurate alignment, stable performance, and the desired characteristics for a wide range of applications.

To advance the state-of-the-art photon sources, Fraunhofer established the Fraunhofer Cluster of Excellence Advanced Photon Sources (CAPS). This cluster pushes the state-of-the-art laser technology and encompasses a wide range of activities, including the generation of multi-kilowatt femtosecond pulses, the generation of secondary source radiation, and the application of these photon processes in scientific and industrial use cases. In the pursuit of major advancements in the Innoslab amplifier concept, our focus lies on advancing high-power short-pulse and ultrashort-pulse lasers, with a remarkable breakthrough of surpassing 1 kW average power for high-beamquality femtosecond pulses. At these powers and beyond robust, efficient, and scalable pulse compression techniques are also required. Using a nonlinear process for pulse compression we have developed a multi-pass compression cell enabling multi-kilowatt average power levels and pulse durations from picoseconds down to the femtosecond few-cycle level for industrial and secondary source applications. Collaborating with other institutes in CAPS, our objective is to elevate the average power of ultrafast lasers to over 10 kW and explore new applications. Access to this capability is provided through the CAPS user facility. New applications comprise the power scaling of coherent EUV radiation via high-harmonic generation (HHG). Notably, we have successfully compressed pulses at a wavelength of 2 µm at 20 fs and 170 W average power, facilitating the generation of even shorter wavelengths through HHG.

Furthermore, the development of laser systems with higher pulse energy and peak power will facilitate the generation of secondary sources such as X-rays, electrons, protons, or neutrons. Looking ahead, high-energy and efficient laser systems hold the potential to contribute to the realization of a laser fusion power plant, offering a clean, safe, and virtually unlimited source of electricity.

Presenting Author

Prof. Constantin Haefner is Managing Director of the Fraunhofer Institute for Laser Technology ILT since 2020, Full Professor and Chair of Laser Technology at RWTH Aachen University, and former Director of the Advanced Photon Technologies Program, National Ignition Facility & Photon Science Directorate at Lawrence Livermore National Laboratory, United States. Haefner is a renowned expert in advanced high-energy laser science and technology, particularly in Inertial Confinement Fusion applications, where he has made pioneering contributions. With his team, he has broken several world records, including the development of the world's most powerful petawatt laser system and the development of the world's highest-energy high-intensity laser. More recently, his research focus has expanded to the development of laser technology and applications for sustainable digital photonic manufacturing. He is a Fellow of the Optical Society of America and has received the Federal Laboratory Consortium (FLC) Tech Transfer Award for outstanding commercialization success, and the R&D100 Innovation Award. He graduated in solid state physics from the University of Konstanz in 1999 and received his PhD from the University of Heidelberg in 2003.

Plasma Dynamics and Future of LPP-EUV Source for Semiconductor Manufacturing (Keynote)

[1,2] Hakaru Mizoguchi, [3]Kentaro Tomita, [1]Daisuke Nakamura,[1]Yukihiro Yamagata, [4]Takeshi Higashiguchi, [5]Atsushi Sunahara, [7]Katsunobu Nishihara, and [1]Masaharu Shiratani

1. *Quantum and Photonics Technology Research Center, Graduate School of Information and Electrical Engineering, Kyushu University, Fukuoka, Japan*
2. *Gigaphoton Inc., Tochigi, Japan*
3. *Division of Quantum Science and Engineering, Graduate School of Engineering, Hokkaido University, Hokkaido, Japan.*
4. *Interdisciplinary Graduate School of Engineering Sciences, Kyushu University, Fukuoka, Japan*
5. *Center for Materials Under eXtreme Environment (CMUXE), School of Nuclear Engineering, Purdue University, Indiana , United States of America*
6. Utsunomiya Univ.
7. *Institute of Laser Engineering, Osaka University, Osaka, Japan*

Recently 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 factories[1)] by ASML. On the other hand, pioneer of this Unique technologies including; combination of pulsed CO_2 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 CO_2 laser more than 27kW at output power in cooperation with Gigaphoton and Mitsubishi Electric[3)]. (Fig.1) 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 Tomson scattering (TS) measurement[4)] . 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. In the EUV Source Workshop we also discuss about experimental data about latest high power experiments.

Fig.1 27kW Driver CO_2 Laser System (Gigaphoton)

REFERENCE

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 (Kyushi 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.)

Presenting Author

Hakaru Mizoguchi is a Fellow of The International Society of Optical Engineering (SPIE), and a member of The Laser Society of Japan and The Japan Society of Applied Physics. He received a diplomat degree in the plasma diagnostics field from Kyushu University in 1982 and joined Komatsu Ltd. He remained a part of the CO2 laser development program in Komatsu for 6 years. Afterwards, he was a guest scientist at Max-Plank Institute Bio-Physikalish-Chemie in Goettingen in Germany from1988 to 1990. Since 1990, he has concentrated on KrF, ArF excimer laser and F2 laser research and development for lithography application. He was the general manager of the research division at Komatsu Ltd. until 1999.
In 1994, he received his doctorate's degree in the high power excimer laser field from Kyushu University in 1994. In 2000 he helped found Gigaphoton Inc. and organized a EUV research group in the EUVA program from 2002 to 2010. Now, in his current position, he is promoting EUV light source development.

He has received the Sakurai award from OITDA Japan in 2018 and the IAAM Scientist Award in the 2020 Advanced Materials Lecture Series.

Scaling Laws of Source Requirements for Optical Inspection in Semiconductor Device Manufacturing (Keynote)

Larissa Juschkin

KLA Corporation, CA, USA

Presenting Author

Larissa Juschkin received her diploma in plasma physics from the Novosibirsk State University, Russia in 1995. In 2001, she received her PhD degree in the field of atomic and plasma physics graduating from the Ruhr University Bochum, Germany. Then, she was employed as the Head of Research & Development by AIXUV GmbH, Germany where she worked on EUV sources and metrology systems until 2005. From 2006 to 2010 she took the lead of the EUV Technology group at the Department of Technology of Optical Systems at the RWTH Aachen University. In 2011, she joined the Plasma Spectroscopy Group at the University College Dublin and worked on the study of short-wavelength radiation from laser-produced plasmas. In 2012, she was appointed to a professorship for Experimental Physics of Extreme Ultraviolet at the RWTH Aachen University. In 2013 she became also the Group Leader of EUV Spectroscopy and Lithography group at the Peter Grünberg Institute 9 Semiconductor Nanoelectronics in Forschungszentrum Jülich in a joint procedure to RWTH professorship. In 2018, she joined KLA Corporation as EUV technologist. Since 2021, she is Program Manager R&D at KLA working on the next generation of wafer inspection tools using broadband plasma radiation. Her scientific focus and research activities combine plasma physics and plasma-based radiation sources with modern nanotechnology applications, especially in the fields of nanostructuring, high-resolution measurement technology and defect detection. She published more than 100 scientific articles and received several patents.

Resolving and Improving the Interfaces of Short-Wavelength Multilayers – EUV and Beyond (Keynote)

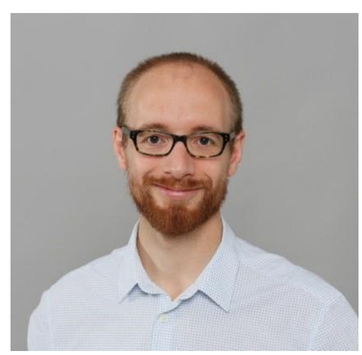
Marcelo Ackermann

University of Twente

Nanometer-level d-spacing multilayers are key optical elements with applications from EUV lithography at 13.5 nm and beyond, and as X-ray optical elements for X-ray fluorescence and astronomical instruments. In all these applications, the quality of the thin films, but most importantly the sharpness of the interface between the layers is key to achieving high reflectivity. Roughness, intermixing and compound formation at these interfaces result in reflectivity losses. In order to improve these interfaces, metrology is needed to resolve on the atomic level, what the driving mechanisms are that lead to reflectivity loss. At the sub-nm scale, a single technique is often insufficient to fully understand the physics of intermixing: Whereas TEM and XRR can resolve the local electronic density, XPS is optimal to highlight compound formation. We demonstrate that only a combination these techniques can truly resolve the interface. In addition, we have developed a novel capability to resolve buried interfaces with LEIS – using a full modelling of the LEIS signal outside the surface peaks – offering atomic density resolution rather than electronic.

For ultra-thin W/Si multilayers – key for the Soft X-ray regime, this combination of techniques shows that the interaction between W and Si results in WSi_x formation, leading to poor optical performance. The introduction of ultrathin 0.1 nm B_4C diffusion barriers shows clear improvement in reflectivity, and through the combination of these multiple surface-sensitive techniques we can directly explain how the barriers contribute to a higher reflectivity.

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.

Digital Solutions for Optics and Laser Technology (Keynote)

Carlo Holly[1,2], Annika Völl[1], Marcel Prochnau[1], Sascha Brose[1,2], Jochen Stollenwerk[1,2], Peter Abels[2], and Cord Fricke-Begemann[2]

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

Digital solutions in combination with innovative laser beam sources, optical systems, sensors and advanced systems technology offer a holistic approach to increase the productivity, efficiency and quality in laser-based manufacturing. Based on advanced optical systems application-adapted intensity distributions are realized, for instance with free-form optics and diffractive optical neural networks. Productivity increases are achieved through adapted process control or parallelized optical systems, for example with multi-beam optics.
At Fraunhofer ILT software and systems are developed that link the real and digital worlds to unlock intelligent cyber-photonic systems in production and for digital business models. New methods and algorithms based on artificial intelligence play a central role for process monitoring, self-learning systems and in measurement technology. In the field of material analytics, we develop systems that classify materials for recycling and the circular economy.

Presenting Author

Prof. Dr. Carlo Holly is professor of Optical Technologies at the RWTH Aachen University. He and his chair, the Chair for Technology of Optical Systems TOS, work in close collaboration with the Fraunhofer Institute for Laser Technology ILT in Aachen, where he is also head of the department Data Science and Measurement Technology. His areas of research include optical systems, computational optics, EUV technology, and digital photonic production. Prof. Holly received the diploma in mechanical engineering, the B. Sc. in physics and the M. Sc. in theoretical particle physics, as well as the Ph.D. degree (Dr. rer. nat.) from RWTH Aachen University. In 2017 he joined TRUMPF Photonics in Princeton, USA, where he worked on the development of high-power semiconductor lasers. In 2020, as Head of R&D Photonics he worked on optical systems and photonics integration for non-invasive glucose measurement devices at DiaMonTech AG in Berlin. In 2021 Prof. Holly became full-time professor at the RWTH Aachen University.

Lasers and Building Blocks for Secondary Sources (Keynote)

Torsten Mans

Trumpf

Presenting Author

Torsten Mans studied physics at the RWTH Aachen and the University of Manchester. During his thesis he built the first InnoSlab amplifier and obtained later his doctorate at the Fraunhofer Institute for Laser Technology (Aachen) in the field of ultrashort pulse laser amplification. He is co-founder of AMPHOS GmbH which joined the TRUMPF group in 2018. Currently he is product manager for secondary sources at TRUMPF Laser GmbH, Schramberg.s.

A Vacuum Utraviolet Frequency Comb for the Excitation of the 229-Thorium Isomer

Stephan H. Wissenberg[1,2,3], Johannes Weitenberg[1,4], Mahmood I. Hussain[3], Peter Rußbüldt[1], Hans-Dieter Hoffmann[1], Constantin L. Häfner[1,2]

[1]Fraunhofer Institute for Laser Technology ILT, Aachen, Germany
[2]RWTH Aachen University, Chair for Laser Technology LLT, Aachen, Germany
[3]Ludwig-Maximilians-University Munich LMU, Am Coulombwall 1, 85748 Garching, Germany
[4]Max-Planck Institute of Quantum Optics MPQ, Hans-Kopfermann-Straße 1, 85748 Garching, Germany

High-harmonic generation (HHG) with lasers provides a possibility to build temporally and spatially coherent vacuum ultraviolet (VUV) and extreme ultraviolet (EUV) light sources. To account for the low conversion efficiency of HHG high power lasers can be used. Furthermore, for high repetition rates an enhancement resonator can additionally boost the efficiency. This presentation will report on a tunable frequency comb in the VUV, which we are currently setting up. It consists of a high-power infrared frequency comb (200 W, 1050 nm), a nonlinear pulse compression unit (50 fs) based on multi-pass-cell spectral broadening and an enhancement resonator (5 kW circulating). To extract the high harmonics from the enhancement resonator we use a non-collinear outcoupling scheme. This frequency comb will be used to optically excite the nuclear transition in 229-Thorium for the first time, and it will be suitable for the operation of a nuclear clock. Such a clock has applications in fundamental physics and can potentially reach a higher precision than atomic clocks.

Presenting Author

Stephan H. Wissenberg is a scientist at Fraunhofer ILT and is pursuing a Ph.D. at RWTH Aachen University. He studied physics at the universities of Düsseldorf (HHU) and Munich (LMU). Since 2018, he has worked in the Lasers and Optical Systems department at Fraunhofer ILT. His research includes resonator assisted HHG and its limitations due to the presence of plasma in the HHG enhancement resonator.

Laser Driven Secondary Particle Generation: An Overview

Rolf Wester

Fraunhofer Institute for Laser Technology ILT, Aachen, Germany

The electromagnetic field of high-power laser beams is capable of accelerating electrons to energies in the MeV range (even many GeV are possible in so-called wakefield accelerators). The high-energy electrons can also lead to the acceleration of ions, and their interaction with charges produces X-rays and γ beams. High-energy ions and γ beams can produce neutrons. 1eV photons can thus produce a large number of particles with energies far exceeding this energy. An overview of the generation of these particles and the necessary laser parameters is given.

Presenting Author

Rolf Wester received his diploma in physics from the Technical University of Darmstadt in 1983. In 1987, he received his doctorate from RWTH Aachen University. In the same year he moved to Fraunhofer ILT, where he worked until his official retirement. In the early years of his career, his main fields of work were plasma and discharge physics, then laser physics and optics, among others. He developed numerical tools for simulating lasers and nonlinear three-wave mixing based on geometrical and physical optics.

A pathway to Commercial Applications for Laser-Wakefield Accelerators

B. Manuel Hegelich

TAU Systems Inc. and 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. TAU Systems, Inc., aims to integrate those advances into a single system, allowing a transition from the laboratory to the market. We will present our current plans to utilize such laser systems to generate high-energy electron beams as drivers for table-top synchrotron-like x-ray sources and compact EUVX free-electron laser systems for semiconductor R&D and metrology, medical and material science applications. We will show recent advances in wakefield target technology, demonstrating for the first time > 10 GeV electrons from a laser wakefield accelerator and how this enables laser-driven XFELs, 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 ion and electron energies generated with a laser.

Novel opportunities of laser-driven neutron and hard X-ray sources entering the market

Dr. Marc Zimmer

Focused Energy GmbH, Darmstadt

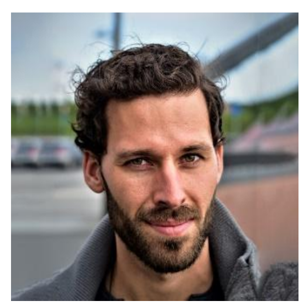
Neutrons are a valuable tool for non-destructive material investigation as their unique way of interacting with materials provides complementary information to x-ray based interrogation. With neutrons it is possible to analyze the internal structure of components, even if shielded by metals, they can determine the material composition of objects and even measure the atomic structure of chemical or biological substances. So far, most neutron applications have been limited to large-scale facilities such as nuclear research reactors, spallation sources, and accelerator-driven neutron sources.

With the technological evolution of modern-day lasers and advances in laser-driven particle acceleration, laser-driven neutron sources have reached a development stage where they become of interest to industry. In the next years this technology will be able to provide the same diagnostic capabilities, previously limited to the large-scale research facilities, as a transportable solution at the size of a shipping container. As a significant benefit, these source types can provide neutrons and MeV x-rays at the same time, opening new possibilities in non-destructive material analysis techniques to a wide range of customers [1]. Within this talk Dr. Marc Zimmer from Focused Energy gives an overview on this new arising technology and its potential for applications.

[1] Zimmer, Marc, et al. "Demonstration of non-destructive and isotope-sensitive material analysis using a short-pulsed laser-driven epi-thermal neutron source." *Nature communications* 13.1 (2022): 1173.

Presenting Author

Dr. Marc Zimmer has a background in laser-plasma as well as nuclear physics and has led the efforts of laser-driven neutron and x-ray production in Darmstadt over the last years. He has demonstrated the first applications with laser-driven neutrons in his PhD thesis and has worked on bringing this type of radiation to the commercial market since. After his time as a postdoc at TU Darmstadt he joined Focused Energy in 2021 as the Head of Laser-Driven Radiation sources where he is responsible for creating a product out of this novel radiation sources.



Coherent EUV Metrology Based on High Harmonic Generation

Travis Frazer

Kapteyn-Murnane Laboratories, Boulder, CO, USA

Coherent, ultrafast EUV light from high harmonic generation (HHG) offers a powerful tool for a variety of metrologies. By directly up-converting IR-vis drive lasers via its extreme nonlinear process, HHG provides laser-like EUV beams with full spatial coherence and down to attosecond pulse durations. These unique properties enable several metrology techniques, including lensless nanoscale imaging [1], ultrafast magnetic spectroscopy [2], and chemical-specific 3D reflectometry [3]. Tabletop HHG systems provide a complementary resource for these experiments alongside facility-scale light sources.

In this talk, I will survey coherent EUV metrology using KMLabs HHG sources and similar setups at the University of Colorado. KMLabs has spent over a decade developing HHG into a reliable EUV source for demanding measurements, such as those I will discuss. I will also present near-term scaling opportunities for HHG sources. Specifically, using longer wavelength IR drive lasers pushes the harmonics generated into the water window and even the keV photon energy range, opening new possibilities in soft x-ray metrology [4].

[1] Gardner, et al., *Nat. Photonics* **11**(4), 259-263 (2017). dx.doi.org/10.1038/nphoton.2017.33
[2] Tengdin, et al., *Sci. Adv.* **6**(3), eaaz1100 (2020). DOI:10.1126/sciadv.aaz1100
[3] Tanksalvala, et al., *Sci. Adv*. **7**, eabd9667(2021). DOI:10.1126/sciadv.abd9667
[4] Popmintchev, et al., *Science* **336**, 1287-1291 (2012). dx.doi.org/10.1126/science.1218497

Presenting Author

Travis Frazer is a Research Scientist at Kapteyn-Murnane Laboratories, where he manages EUV product development and laser source research. He earned his PhD in the Kapteyn-Murnane research group at JILA in the University of Colorado, Boulder, on the topic of applying coherent EUV beams to studying nanoscale thermal and mechanical properties of materials relevant to the semiconductor industry and beyond. Before returning to Colorado for his current position, he was a Postdoc at Argonne National Laboratory in Illinois, USA. There, he used synchrotron and XFEL light sources for coherent imaging and ultrafast diffraction studies of quantum and energy materials.

Roadmap to High-Brilliance EUV and SXR Sources

Dr. Robert Riedel

Class 5 Photonics GmbH, Hamburg, Germany

In recent years, the capabilities of extreme ultraviolet (EUV, 13.5 nm) and soft-X-ray (SXR, >285 nm) sources have greatly expanded, presenting transformative opportunities in the realms of metrology and advanced material studies. These technological advancements have the potential to provide deeper insights into the electron dynamics of photoresists and semiconductors. Such understanding is paramount in surmounting existing limitations and achieving superior resolution in lithographic processes.

The push towards these advancements is propelled by the combination of high-power femtosecond lasers with advanced nonlinear technologies. Among these, optical-parametric chirped-pulse amplifiers (OPCPA) and multi-pass cells (MPC) have shown significant promise. When synergized with high-power Yb-doped laser systems, these technologies have achieved breakthroughs in performance, reliability, and cost-effectiveness. The laser pulses generated by these state-of-the-art systems are of such intensity that they are now integral to experiments in high-harmonic generation (HHG). For HHG to effectively cater to the EUV and SXR ranges, specific driver wavelengths are mandated—approximately 1 µm for the EUV range and exceeding 1.6 µm for the SXR spectrum.

In this context, Class 5 Photonics stands at the forefront of innovation. We are excited to introduce and discuss our latest concepts and findings. This includes our compact 1 µm-wavelength lasers, which boast an impressive output of over 250 W and mJ-level pulse energies. On the larger scale, our mid-infrared systems operating at a 3 µm-wavelength demonstrate over 10 W output power with pulse energies at the 10 mJ level. Complementing these discussions, we will also present our initial results in EUV generation.

Presenting Author

Robert Riedel graduated in 2010 from Friedrich-Schiller-University Jena in Physics with focus on photonic integrated circuits and femtosecond laser micromachining (Institute of Applied Physics). He received his PhD in 2013 at the University of Hamburg for his work at DESY, developing high-power femtosecond Lasers and EUV/soft- X-ray sources and metrology tools. While continuing his work at DESY from 2013 2015, he founded Class 5 Photonics with colleagues working in Hamburg, Germany and Stanford, USA. Together with his team, he received several innovation awards.

Fabrication of (complex) Periodic Patterns by Talbot Lithography with Compact EUV sources

Bernhard Lüttgenau[1], Lars Lohmann[1], Sascha Brose[1,2], Serhiy Danylyuk[2], Jochen Stollenwerk[1,2], and Carlo Holly[1,2]

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

Dense periodic nanostructures with feature sizes below 100 nm are essential for numerous industrial and scientific applications, such as photoresist qualification for achieving high resolution and the production of metamaterials, biosensors, quantum dot arrays, and artificial crystals. To address these applications, compact nanopatterning tools using EUV radiation are a promising option. The developed compact EUV exposure tool at RWTH Aachen University employs a discharge-produced plasma (DPP) EUV source for large-area nanopatterning and industrial EUV photoresist qualification. Talbot lithography has proven to be an effective method for this setup, utilizing all diffraction orders from a transmission grating for efficient patterning.

In this presentation a rigorous simulative and experimental evaluation of phase-shifting masks for Talbot lithography at EUV wavelengths is shown. The goal is to increase both resolution and pattern complexity by optimizing the transmission mask geometry and material system, ultimately enabling sub-30 nm patterning. These advancements pave the way for a compact EUV exposure setup suitable for both industrial EUV photoresist qualification and large-area nanopatterning for various scientific applications.

Presenting Author

Bernhard Lüttgenau is a PhD student at RWTH Aachen University. He received his bachelor's and master's degrees in physics, majoring in the subject of solid-state physics. Since 2019, he is working in the EUV technology group at the Chair for Technology of Optical Systems. His research topics include EUV interference lithography with compact EUV sources and related process technologies. He has authored and co-authored 10 publications by now.

High Flux XUV Beamlines for Imaging and Spectroscopy

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

Active Fiber Systems GmbH, 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 source, 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.

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.

High performance high harmonic sources, imaging and metrology in the EUV

Jan Rothhardt

Helmholtz Institute Jena, Friedrich-Schiller University and Fraunhofer IOF, Jena

High harmonic sources offer unique opportunities for imaging and metrology in the extreme ultraviolet spectral region (EUV): The short wavelength enables nanoscale resolutions, while the µm-scale penetration depth allows to look inside complex samples and uncover their internal structure. In addition, a detailed and highly precise characterization of optics or EUV lithography masks can be performed "at wavelength" with compact table-top setups.
I will present recent advances in the field of high average power high harmonic sources sources, including a record-demonstration of 13 mW coherent power, and their applications to table-top lensless imaging and metrology.
By combining a cutting-edge source, structured illumination and computational imaging, we achieved sub-20 nm spatial resolution and quantitative images with high amplitude and phase accuracy at 13.5 nm wavelength. Those images allow for precise metrology as well as for elemental identification on the nanoscale.
As first application examples, we demonstrate nanoscale chemical mapping on a microelectronic structure as well as quantitative amplitude- and phase-metrology of an EUV diffusor.
Our demonstrations show that high precision quantitative nanoscale EUV imaging and metrology is feasible with compact table-top setups and provides numerous opportunities complementary to existing techniques.

Presenting Author

Jan Rothhardt is head of the "Soft X-ray spectroscopy and microscopy group" at the Helmholtz-Institute in Jena. He received his PhD in Physics in 2010 and his Habilitation in 2021. His work is focused on table-top EUV/X-ray sources and their application to spectroscopy, microscopy and metrology. He published more than 90 articles in scientific journals and is author of several book chapters and patent applications. In 2020 his work was honored with the Röntgenpreis for the development and application of compact high photon flux EUV and soft X-ray sources.

The Last Light Source

Erik R. Hosler

xLight, Inc.

Light drives innovation – the wavelength, the power, the intrinsic qualities. From the mask shop to the packaging fab, from lithography to metrology, each technology node has relied on light invention to enable scaling, process control, reliability, and even ensuring supply chain security. However, the increasing cost and complexity of new light sources to meet industry demands has become prohibitive, leading to stagnation in technology development and reliance on the status quo in terms of the light available and the applications it permits. Now, a leap is required to the ultimate generation light source that will serve the semiconductor industry indefinitely, providing low-cost EUV as well as any wavelength required for manufacturing and R&D applications. But what would such a light source look like? What would be possible? Surprisingly, the groundwork has already been laid and the future of light source technology has never been brighter.

Presenting Author

Erik Hosler is the Founder and CEO of xLight Inc, a semiconductor equipment company focused on developing the ultimate light source for the industry. Previously, he was the patterning lead and strategist for PsiQuantum LLC, a silicon photonics quantum computing company as well as the Lead EUV Technologist at GlobalFoundries, responsible for driving industrialization efforts of EUV technology for high-volume manufacturing readiness across all aspects of the infrastructure. He is an expert in the field of laser spectroscopy, vacuum technologies, EUV light sources and metrology.

Highly efficient generation of EUV light using 2-um drive laser light

O. O. Versolato, Y. Mostafa, D.J. Engels, L. Behnke, Z. Bouza, and W. Ubachs

ARCNL, Amsterdam, The Netherlands

We present tin plasmas driven by solid-state 2 μm lasers as an efficient light source for extreme ultraviolet light (EUV) lithography. We achieve high conversion efficiencies by optimizing the drive laser's temporal and spatial profiles to generate uniform temperature plasmas from tin microdroplets. The spatial and temporal uniformity of the laser's intensity profiles is the main determinant of high efficiency sources. We scale the laser pulse duration, spot size and intensity to demonstrate high EUV energy output. The EUV emission source size is studied under similar parameter range. We show that the tin plasma driven by 2 μm laser light is a promising alternative for EUV lithography applications.

Presenting Author

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

Modeling the Hundreds-of-nanoseconds-long, Joule-level Irradiation of Tin droplets with a 2 µm-wavelength Laser for Future EUV Lithography

Stan de Lange[1,2], D. Hemminga[1,2], J. Gonzalez Munoz[1,2], Y. Mostafa[1,2], O. O. Versolato[1,2], and John Sheil[1,2]

[1]*Advanced Research Center for Nanolithography (ARCNL), Amsterdam, The Netherlands*
[2]*Department of Physics and Astronomy, and LaserLaB, Vrije Universiteit, Amsterdam, The Netherlands*

We present tin plasmas driven by solid-state 2 µm lasers as an efficient light source for extreme ultraviolet light (EUV) lithography. We achieve high conversion efficiencies by optimizing the drive laser's temporal and spatial profiles to generate uniform temperature plasmas from tin microdroplets. The spatial and temporal uniformity of the laser's intensity profiles is the main determinant of high efficiency sources. We scale the laser pulse duration, spot size and intensity to demonstrate high EUV energy output. The EUV emission source size is studied under similar parameter range. We show that the tin plasma driven by 2 µm laser light is a promising alternative for EUV lithography applications.

Presenting Author

Stan de Lange studied Physics & Astronomy at the University of Amsterdam, before specializing in theoretical physics in the Master’s. Since 2022, he is pursuing a PhD as part of the Plasma Theory & Modeling group under Dr. John Sheil at the Advanced Research Center for Nanolithography (ARCNL), where he uses hydrodynamic simulations to understand the properties of the EUV source plasma and optimize its yield.

Enhancement of Sn plasma EUV Emission by Double-sided Laser Illumination

Yotam Mazuz-Harpaz

L2X Labs, Jerusalem, Israel

Advancements in state-of-the-art nanolithography technology over the past decade have been raising an ongoing demand for improvement of the power and efficiency of extreme-ultraviolet (EUV) light sources, that stand at its heart. This study introduces a novel double-sided laser illumination scheme aimed at enhancing EUV emission from such a laser-produced Sn plasma source. Using a solid-state laser, experiments were conducted with suspended solid Sn targets of varying thicknesses, evaluating the resulting effect on EUV output intensity. A significant increase in EUV emission was observed with double-sided illumination, particularly for thinner targets. For targets with thicknesses of 60 and 20 nm, an increase between 50% and 150% in EUV emission was detected in comparison to single-sided illumination. Extrapolating to a long laser pulse that burns through the target, the enhancement is projected to be 17% for a 300nm thick target. These results highlight a promising way for further improvement of output power and energy efficiency in next-generation EUV light sources.

Presenting Author

Yotam Mazuz-Harpaz is a researcher in L2X Labs, working on advanced approaches for laser-plasma interaction in laser-produced Sn plasma for EUV sources. From 2014-2023 he worked on M.Sc. and a Ph.D. (pending approval) in physics from the Hebrew University of Jerusalem, Israel. He studied collective quantum phenomena of dipolar electron-hole pairs in cold semiconductor nanostructures. From 2020-2022 he was the VP of Physics and Engineering at Urecsys ltd.

S55

EUVL Extension - Blue-X: Status and Challenges Ahead

Vivek Bakshi

EUV Litho, Inc.

As high NA EUVL scanners are getting ready for introduction in HVM, the focus now turns to what comes next! In order to continue to extend Moore's Law, our current choices are either to increase the numerical aperture (NA) of EUVL scanners or decrease the source wavelength once again. Options of increasing the NA (Hyper NA) or decreasing the wavelength (Blue-X) are challenging. Each comes with its own set of technical and business obstacles. In this short talk, I will give an overview of these challenges for both cases and share my opinions for a sustainable path forward for the extension of Moore's Law.

Presenting Author

Dr. Vivek Bakshi founded EUV Litho, Inc. in 2007. In addition to organizing the conferences hosted by EUV Litho, Inc, he provides consulting services in the areas of EUV lithography (EUVL) and general lithography to investors, funding agencies, universities, national labs and suppliers.

Currently, Dr. Bakshi is an Adjunct Professor in the School of Physics, University College Dublin, Ireland. He is a member of the Editorial board and Associate Editor of JM3 (SPIE Journal of Micro/Nano Lithography, MEMS and MOEMS). Previously, he was a Senior Member of the Technical Staff in SEMATECH's Lithography Division. Recognized as an expert in EUV source technology on a global scale, he is widely quoted in trade media on EUVL-related topics

S61

EUV-induced Plasma in Lithographic Scanner

Mark van de Kerkhof [a,b]

[a.] *ASML Netherlands B.V., Veldhoven, The Netherlands*
[b] *Department of Applied Physics, Eindhoven University of Technology*

In the past years, EUV lithography scanner systems have been widely adopted for manufacturing of state-of-the-art Integrated Circuits (IC), with critical dimensions down to 10 nm. This technology uses 13.5 nm EUV radiation, which is shaped and transmitted through a near-vacuum H_2 background gas. This gas is excited into a low-density H_2 plasma by the EUV radiation, as generated in high-frequency pulsed mode operation by the Laser-Produced Plasma (LPP) in the EUV Source.

Thus, in the confinement created by the walls and mirrors within the scanner system, a reductive plasma environment is created that must be understood in detail to maximize mirror transmission over lifetime and to minimize molecular and particle contamination in the scanner. Besides the irradiated mirrors, reticle and wafer, also the plasma and radical load to the surrounding construction materials must be considered. This presentation will provide an overview of the EUV-induced plasma in scanner context. Special attention will be given to the plasma parameters in a confined geometry. It will be shown that plasma confinement and resulting contributions from secondary electron emission delay the formation of the plasma sheath and thereby reduce the peak ion energies, to below the sputtering threshold for mirrors and construction materials. Also, the spectrum of the EUV Source may be relevant in this respect. Furthermore, for a confined pulsed plasma with a pulse period shorter than the decay time of the plasma, the plasma will consist of a quasi-steady-state cold background plasma, and periodic transient peaks in ion energy and ion flux. In terms of modeling, this means no assumptions can be made on the electron distribution functions, and a (Monte-Carlo) Particle-in-Cell (PIC) model is needed. We will present an extension of the PIC model approach to complex 3D geometries and to multiple pulses, by using a Hybrid PIC-diffusion approach.

Presenting Author

Mark A. van de Kerkhof is the manager for EUV Research Projects at ASML, based in Veldhoven, The Netherlands. He received an M.Sc. in Applied Physics from Eindhoven University of Technology in 1995, and recently received a PhD in Applied Physics, also at Eindhoven University of Technology. He began his career at ODME, working on the development of the DVD mastering process. In 1999 he joined ASML as senior designer and later project manager, working on development of miscellaneous sensors as well as projection optics in both DUV and EUV scanners. He currently is Director for EUV projects at ASML Research, as well as assistant professor at Eindhoven University of Technology.

He holds over 100 patents and authored or co-authored more than 50 scientific papers. He presents frequently at conferences about both photolithography and plasma physics.

EUV-induced Plasma as an Intermediate State for EUV-beam Metrology

Job Beckers

Eindhoven University of Technology, Eindhoven, the Netherlands

Diagnosing beams of ionizing radiation has been subject of research as long as applications in this field exist. Many techniques to reveal temporal and spatial information about a beam of ionizing photons are intrusive. To minimize this intrusiveness, plasma may be a suitable intermediate state for novel metrological equipment to be developed.

The in this contribution elaborated diagnostic is based on using a very small fraction of a beam of Extreme Ultraviolet (EUV) photons, here generated by a discharge produced plasma (DPP) EUV source, to partially photo-ionize a low-pressure background gas. As a result, this background gas is turned into a so-called EUV-induced plasma which then can be further characterized by state-of-the-art plasma diagnostics [1].

For this characterization, the beam of photons is sent through a cylindrical metal pillbox cavity filled with a sensing gas at low pressure. The free electrons in the plasma induced in this cavity are probed by having them interacting with a standing electromagnetic wave in the microwave frequency range (a few GHz) [2] and optionally with a steady state magnetic field [3]. Tracking the resonance frequency of this standing wave temporally resolved, reveals information about the radiation beam in terms of power, alignment, and stability. This contribution elaborates on the physical principles of the method and highlights the newest developments towards in-line beam monitoring.

[1] J. Beckers et al 2019 A*ppl. Sci. 9*(14), 2827
[2] J. Beckers *et al* 2019 *J. Phys. D: Appl. Phys.* **52** 034004
[3] R. Limpens *et al* 2021 *J. Phys. D: Appl. Phys.* **54** 435205

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.

Investigations of EUV-induced low density hydrogen plasma in a high-intensity irradiation setup

Adelind Elshani[1], Niklas Pengemann[2], Rolf Wester[3], Ismael Gisch[1], Sascha Brose[1,3], Hendrik Kersten[2], Jochen Stollenwerk[1,3], Thorsten Benter[2], and Carlo Holly[1,3]

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

[2]University of Wuppertal – Chair for Physical and Theoretical Chemistry Gaußstraße 20, 42119 Wuppertal, Germany;

[3]Fraunhofer ILT - Institute for Laser Technology, Steinbachstr. 15, 52074 Aachen, Germany

[3]Fraunhofer ILT - Institute for Laser Technology, Aachen, Germany

The interaction of the intense EUV radiation with hydrogen gas atmospheres leads to the formation of a low-density hydrogen plasma. A fundamental understanding of the underlying chemical processes is necessary but is complicated due to the complexity of the plasma formation process in a given residual gas composition.

The developed stand-alone high-intensity irradiation setup (EUV-HIEX) allows to reduce the complexity significantly and to investigate the fundamental dependencies with mostly unbiased parameters. High-intensity exposures at industrial relevant intensity levels can be achieved with high spectral purity around 13.5 nm, a high vacuum quality and a symmetric vacuum chamber geometry. By coupling to a high-resolution time-of-flight mass spectrometer, a detailed investigation of the plasma-induced chemistry is enabled. Furthermore, a modeling framework is developed to couple experimental data with theoretical models to achieve a better understanding of the underlying processes.

Presenting Author

Adelind Elshani 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 EUV material interaction in gas atmospheres with compact EUV sources and related diagnostic tools.

Toward a Direct Comparison of Measured and Modeled EUV Spectra

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, Hokkaido, Japan*
2. *Center for Materials Under eXtreme Environment (CMUXE), School of Nuclear Engineering, Purdue University, Indiana, USA*
3. *Institute of Laser Engineering, Osaka University, Osaka, Japan*
4. *Faculty of Engineering, Osaka Metropolitan University*
5. *Kansai Institute for Photon Science (KPSI), National Institutes for Quantum Science and Technology (QST), Kyoto, Japan*

We introduce a new method for directly comparing measured and modeled EUV spectra of laser-produced tin plasma. A flat-field grazing incident spectrometer (GIS)with a toroidal mirror was used to provide 1D-spatially resolved EUV spectra along the planar target normal. Simultaneously, Collective Thomson Scattering (CTS) was employed to measure spatial and temporal resolved plasma density and temperature data in Sn-LPP [1], during the drive laser irradiation.

Utilizing the CTS data, we calculate EUV spectra using modeling results of emissivity and opacity [2], which are then compared with the spectra provided by GIS. This combination of CTS and GIS measurements enables a direct comparison between experimental observations and theoretical predictions, advancing understanding of plasma dynamics and emission characteristics.

1. Tomita, K. *et al.* Observation of plasma inflows in laser-produced Sn plasma and their contribution to extreme-ultraviolet light output enhancement. *Sci Rep* **13**, 1825 (2023).
2. Sasaki, A. et al. Modeling of radiative properties of Sn plasmas for extreme-ultraviolet source. Journal of Applied Physics **107**, 113303 (2010).

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.

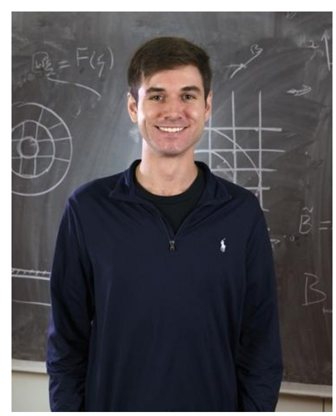
Acceleration of Energetic Ions in Laser-Driven Tin Plasma EUV Sources

Will Fox

Princeton University, Princeton, NJ, USA

Laser-driven tin plasmas are driving new-generation nanolithography as sources of extreme ultraviolet (EUV) radiation. A major challenge facing industrial EUV source development is the acceleration of damaging energetic ion debris during the laser-plasma interaction. Understanding of the plasma dynamics and ion acceleration mechanisms in these sources could provide critical insights for designing debris mitigation strategies in future EUV sources. Here we perform fully kinetic modeling of tin-EUV sources using one-dimensional particle-in-cell simulations. An inverse-bremsstrahlung heating operator is used to model the laser-plasma interaction, thermal conduction is included through a Monte-Carlo Coulomb collision operator, and the simulations are compared with analogous radiation hydrodynamics simulations to benchmark the fluid scale evolution. Significant two-fluid effects are seen in the leading edges of the ablated plasma flows, which are found to be regions of strong energization. A collimated flow of energetic ions is produced with energies and spectral shape that resemble experimentally measured distributions. Through an analysis of self-consistent particle trajectories, we find the dominant acceleration mechanism to be a large-scale electric field driven mainly by the electron pressure gradient, with minor contributions from the thermal force and particle collisions. We discuss the implications of these results for debris mitigation in EUV sources.

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.

High-Resolution Spectroscopic Imaging of Atoms and Nanoparticles in Thin Film Vaporization

D.J. Engels, R.A. Meijer, H.K. Schubert, W.J. van der Zande, W. Ubachs, and O.O. Versolato

ARCNL, Amsterdam, the Netherlands

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. This results in a spatially resolved spectrum for each pixel with a 10 μm and 10 cm^{-1} resolution respectively. An example image can be seen below. Each spectrum contains many atomic resonances of neutral tin and a broadband contribution from nanoparticles.
We use the resonances to reveal a homogeneous temperature profile throughout the vapor of around 3000 K (below, middle). We also obtain spatially resolved atomic densities (below, right) and combine this with the local temperature to create an electron density map.

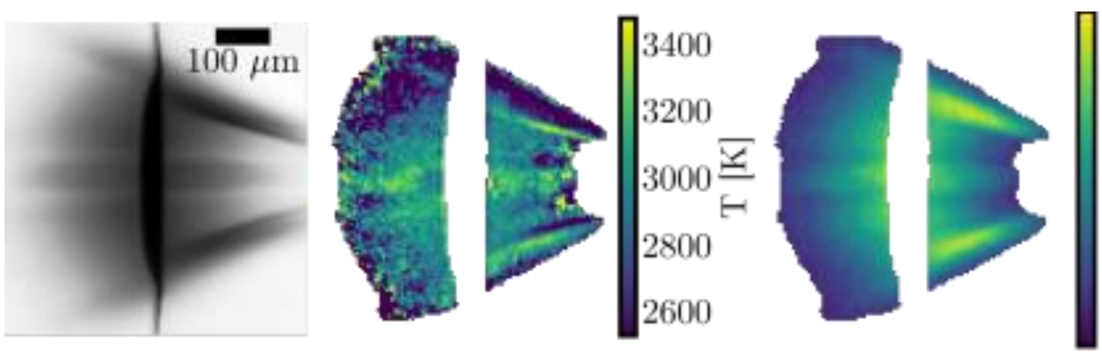


Fig. 1: Spatial resolved composition of tin vapor. On the left, a processed example image. In the middle, the temperature map created for this vapor. On the right, the relative density map for the same vapor.

Presenting Author

Dion Engels recently graduated Cum Laude from the Eindhoven University of Technology, obtaining a double Master's degree in Applied Physics and Nuclear Fusion. As a part of these degrees, he did an internship at the Max Planck Institute for Plasma Physics. He also completed a year-long graduated project in the EUV Plasma Processes group at ARCNL. Since August 2022, Dion has been a Ph.D. candidate in the EUV Plasma Processes group of ARCNL continuing similar research.

EUV LPP Light Source based on Fast-rotating Target: Target Material Variants and Way to Increase Spectral Brightness.

Mikhail Krivokorytov, Alexander Tovstopyat, 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

The diffractive optical systems based on zone plates are well known technique for high spatial resolution imaging. Zero-aberration, diffraction limited illumination points for high detection sensitivity make them ideal for actinic EUV inspection and metrology. Typically, the use of zone plates implies the use of monochromatic light. Synchrotron radiation is ideal for diffractive optical systems, but it is unavailable to small-scale laboratories. With the advances of ultrafast laser technology, EUV light sources based on the high-order harmonic generation (HHG) have become widespread, but they often have difficulties to provide enough photon flux to meet the needs of the industry. The use of classical xenon/tin based LPP and discharge EUV sources requires preliminary monochromatization of the radiation and leads to significant EUV losses.

This report presents the results of spectral brightness measurements obtained on a TEUS type EUV LPP light using a fast-rotating target [1]. We compare different target materials and demonstrate that it is possible to concentrate emission energy in single line @13.5 nm with $\lambda/\delta\lambda$ >1000 resulting in spectral brightness up to 10 kW/nm*mm^2*sr.

[1] Mikhail Krivokorytov et al. "TEUS: high-brightness EUV LPP light source based on fast rotating target: product overview and specifications" International Conference on Extreme Ultraviolet Lithography 2021.

Presenting Author

Mikhail Krivokorytov is the Head of EUV Research Department at ISTEQ EUV. After completing a Ph.D. in Physics and Mathematics at Moscow Institute of Physics and Technology (MPTI) in 2014, he joined EUV Labs LLC as a Senior Researcher, where he worked in the field of interaction of high intensity laser radiation with matter, diagnostics of laser produced plasma with a special focus on the design of light sources. In 2023 Mikhail joined the ISTEQ EUV team.

Development of a Laser-induced Plasma EUV Light Source Suitable for Inspection tools

Masayasu Nishizawa, Keitaro Hayashida, Takayuki Ishida, Hiroki Miyai, Atsushi Tajima, Haruhiko Kusunose

Lasertec Corporation, Yokohama, Japan

In 2019, Lasertec released ACTIS, the world's first APMI (Actinic Patterned Mask Inspection) tool capable of detecting all types of printable defects present on EUV masks with high sensitivity and high throughput. ACTIS has been delivered to Lasertec's customers and used at both fabs and mask shops in leading-edge semiconductor device production using EUV lithography.

As the advancement of EUV lithography enables the further scaling of semiconductor devices, there arises demand for more sophisticated mask defect inspection. To meet this demand, Lasertec has developed a new EUV light source best suited for APMI needs.

To improve sensitivity and throughput for defect inspection, you need to increase the brightness of illumination on the mask, but you also need to avoid excessive heat load to prevent heat-sensitive pellicles from being damaged. Lasertec has developed a light source that illuminates the field of view with high brightness without causing excessive heat load on masks and pellicles. This is made possible by generating a plasma that emits a high-brightness EUV beam with an appropriate shape matching the field of view of imaging optics. In this presentation, we discuss some of the features of the newly developed EUV light source.

Presenting Author

Masayasu Nishizawa is a product leader of EUV light sources developed at Lasertec from 2018. Masayasu received his Ph. D. in materials science and engineering from Waseda University in 1999. From 1999 to 2011, he worked at the National Institute of Advanced Industrial Science and Technology (AIST) developing semiconductor device metrology methods using scanning tunneling microscopy. After working on the development of high-speed atomic force microscopy, he joined Lasertec in 2015.

S73

Optimization of an all Solid-state Driven Discharge Produced Plasma (DPP) EUV source

David Reisman[1], Daniel Arcaro[1], Fred Niell[2], Michael Roderick, Bob Grzybinski[1], Scott Moore[1], and Chris Lee[1]

[1]Energetiq Technology, Inc., Wilmington, MA, USA
[2]Nielltronix, Inc., Tampa, FL, USA

We report on the development of a new discharged produced plasma (DPP) light source, EQ-NEX. The source uses a xenon plasma in a Z-pinch configuration to produce 13.5 nm (±1% BW) radiation. Based on the Energetiq Electrodeless Z-Pinch™ design, the new source is driven by an all solid-state switching configuration that overcomes the limitations of traditional magnetically switched systems. With this new system we demonstrate that both repetition rate and energy per pulse can be greatly increased. Consequently, we have doubled our EUV power output. We will describe efforts to further optimize the system for brightness by using a combination of operation parameters and capillary Z-pinch insert design.

Presenting Author

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

S74

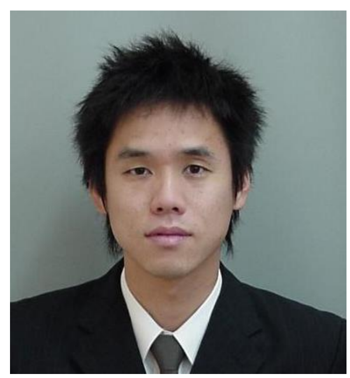
Development Status of Gigaphoton's LPP EUV Light Source for Inspection Systems

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

Gigaphoton Inc., Tochigi Prefecture, 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. Since 2002, Gigaphoton Inc. (GPI) has been developing a laser-produced plasma (LPP) EUV light source. Based on its accumulated high-power LPP technologies, GPI is now developing a EUV light source for inspection tools. This new EUV light source uses a minimum-mass Sn droplet target, a long-lifetime droplet generator with an in-line Sn fuel supply system, a double-pulse laser with a high-precision irradiation control system, and H_2 buffer-gas debris mitigation technology to protect the EUV collector mirror. This EUV light source is expected to be a highly stable operation and has the potential to achieve an annual maintenance cycle. The current EUV light source system has a plasma point brightness of 120W/mm^{2}sr and a repetition rate of 20kHz. A continuous 500-hour test showed no reflectivity degradation of the EUV collector mirror, and a stable EUV energy 3σ-value of 5% with a high availability of 97%. At the conference, we will present the development progress of our EUV light source system.

Presenting Author



Yoshifumi Ueno is a chief manager of Advanced Light Source Development Department at Gigaphoton Inc. He joined the Komatsu Ltd. in 1998. He did a Laser Produced Plasma (LPP) EUV light source research at MIRAI and EUVA Project from 2001 to 2009. He received his doctor degree from Utsunomiya University in 2009. Then he did the LPP physics research as a visiting scholar from Komatsu Ltd. at University of California, San Diego for 2 years. Currently, his work focuses on a system development of a practical EUV light source at Gigaphoton Inc.

S75

Systems for Development and Accelerated Testing of EUVL Components

Jochen Vieker and Klaus Bergmann

Fraunhofer Institute for Laser Technology – ILT, Aachen, Germany

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

The talk will focus on the Fraunhofer high Irradiance Tool (FIT) for testing of optical components. It is based on our proven FS5440 high power EUV source, whose emission is focused on a sample in controllable atmosphere. Using strong vacuum separation and particle mitigation, an extremely low operating pressure at the irradiation position can be achieved without pumping orifices in the vicinity of the focal spot. Thus, clean, unbiased experimental conditions can be achieved. The expected performance of the FIT includes: EUV irradiance >40 W/cm², angle of incidence on sample <5°, spot diameter >1.8 mm and pulse repetition rate up to 2.5 kHz. The talk will follow-up on the Lab-tour from the day before.

Presenting Author

Jochen Vieker received his Diploma (M. Sc. equiv.) in physics in 2011 from Bielefeld University, for his work on high harmonic generation. Since then he has been scientist in the EUV technology group at the Fraunhofer Institute for Laser Technology and finished his PhD in physics in 2019 at RWTH Aachen University for his research on power and lifetime scaling of discharge based EUV sources. He is manager of the R&D projects and architect of ILT’s EUV systems. Fields of interest include fundamental research on EUV sources and secondary sources based on laser radiation as well as their applications.

S76

Characterization and Performance Improvement of Laser and Discharge - driven EUV Sources

Yusuke Teramoto[1], Guido Mertens[1], Ralf Kops[1], Margarete Kops[1], Wilko van Nunspeet[1], Marcel Schneider[1], Klaus Bergmann[2], Fuki Sato[3], Akihisa Nagano[3]

[1] Ushio Germany GmbH, Aachen, Germany
[2] Fraunhofer ILT, Steinbachstrasse 15, 52074 Aachen, Germany
[3] Ushio Inc., Shizuoka, Japan

A LDP source is a plasma EUV source driven by a pulsed high-current discharge. The discharge between Sn-covered rotating disc electrodes in vacuum is triggered by laser pulses. It is operated at up to 10 kHz, and used on an exposure facility and for actinic patterned mask inspection. We studied how the laser pulse influences EUV and fast-ion emission by measuring EUV energy, EUV emission profile, emitted ion energy, and discharge current.

A LPP source is a compact plasma EUV source driven by a laser. The compact LPP source is being developed to provide a multi-purpose light source to various applications. The source was characterized at the plasma and at the intermediate focus (after SPF and collector) by measuring EUV energy, EUV emission profile, and emission spectrum. The latest development progress and insight on both sources will be presented at the workshop.

Presenting Author

Yusuke Teramoto received his 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.

The EUV-LAMP and application in Pellicle Inspection Tools

A. Biermanns-Föth*, C. Pampfer, C. Phiesel, T. Missalla, R. Bruck, R. Lebert

EUV lithography is used for chip volume production. EUV pellicles and dynamic gas lock windows in the scanner are corner stones for the technology. The pellicle is a thin film (≈ 50 nm thick) placed above the patterned surface of the EUV reticle and retains particles that would have otherwise landed on the patterned side of a reticle. As these particles are then out of focus, their impact on the imaged pattern is strongly reduced from the nanometer range to the micron range.

Those thin film components must be qualified in various aspects before being used in production. In particular, the EUV transmission and reflectance at 13.5 nm in the bandwidth used in the scanner have to be quantified over the entire pellicle area such that best quality/ homogeneity for achieving desired CD is verified.

RI Research Instruments GmbH (RI) supports the EUVL infrastructure with actinic metrology and test solutions and components. Based on RIs actinic EUV in-band metrology concept (AIMER™), the EUV Pellicle Reflection and Transmission Tool (EUV-PRTT) has been co-developed with ASML and is used for pellicle production since 2020. In this presentation we will illustrate the main building blocks of the system and explain the working principle that allows to simultaneously measure EUV transmittance values above 90% and reflectance values as low as 0.002% with high spatial resolution and accuracy.

Presenting Author

Andreas Biermanns-Föth is Business Manager for EUV Systems and Photon Instrumentation at RI Research Instruments GmbH. He received his PhD in Physics at the University of Siegen, working on the characterization of semiconductor nanostructures. In his scientific career he has been developing synchrotron-based nano-focusing techniques and novel coherent diffraction methods. After joining RI Research Instruments as project manager in 2014, he has been focusing on developing custom tailored EUV metrology tools for the semiconductor supply chain.

Compact LPP Source for Inspection Application in Semiconductor Manufacturing

Reza Abhari

ETH Zürich

In its continuation of past developments, the recent focus of the team has been on a full and rigorous industrialization of the HVM version of its proven LPP technology in the new large clean room facilities. In addition to its high output brightness at a cost-efficient configuration, this next generation of droplet based LPP EUV source with its fully thermally controlled design features have much greater operational flexibility, continuous operation, actively controlled large normal incidence multi-layer collector assembly, high uptime with fast quick turnaround droplet generator installation and replacement, an efficient fuel (tin) recovery system, as well as a fully integrated high precision robotic arm to partially manage regular servicing of the source without the need for human intervention.

In this presentation, the latest technical and operational improvements in the brightness and operational capability of the LPP light source will be presented. Having previously demonstrated EUV source brightness measurements of about 1000 W/mm2 Sr, the current extendible light source is suitable for mask and wafer inspection systems for many future nodes, lowering technology risks for tool roadmap. The small footprint of the source as well as state of the art platform damping technology ensures that the light source can be seamlessly integrated into most inspection tools. The full system has been designed to be air-shipped in a standard LD7 container, with an integrated housing which packages all the system components including the laser, optics, source and all the control system.

Presenting Author

Light Sources for Metrology Applications

Iris Pilch

Zeiss

Extreme Ultraviolet (EUV) lithography is a technology for high volume manufacturing of semiconductors. In the production process of the lithography technology and of semiconductors are metrology applications essential to ensure the quality of the product.

EUV light sources are a critical component for the overall performance of metrology applications with working wavelength at 13.5nm. Therefore, performance parameters like the stability of spot position or energy per pulse need to be considered as an input parameter for the optical design. When a design is found, other aspects like availability, lifetime and costs play a crucial role whether the application is economically reasonable or not. Since EUV has entered high volume manufacturing, the economic aspects and industrial maturity become key drivers for the realization for metrology applications.

In this presentation, a short information on EUV lithography and its next development will be given, and the main challenges for EUV light sources in industrial metrology applications will be discussed.

Presenting Author

Iris Pilch received her Ph.D. degree from Christian-Albrechts-Universität in Kiel, Germany in 2010 where she studied the dynamics of dust-density waves and dust particles in a complex plasma. After her Ph.D., she joined the Plasma and Coatings Physics Division at Linköping University, Sweden, as a post doc to investigate the growth of nanoparticles in highly ionized pulsed plasmas. Her research interests include plasma physics, complex plasmas, nanoparticle synthesis and the diagnostics of nanoparticles during growth.

Simultaneous Spectroscopy and Imaging of an EUV plasma using Zone-plates Dispersion Matched to Transmission-gratings

Muharrem Bayraktar

XUV Optics Group, MESA+ Institute for Nanotechnology, University of Twente, Enschede, The Netherlands

When combining imaging and wavelength selectivity in EUV plasma metrology, available techniques are usually restricted to broad wavelengths with limited resolution (e.g. pinhole imaging with foil filters) or narrow bandwidths with decent resolution (e.g. multilayer mirror imaging). Combining broadband spectroscopy and imaging in the EUV range is a challenge.

We present the design of an 1D imaging spectrometer incorporating free-standing transmission gratings and zone plates [1]. The spectrometer utilizes transmission gratings for dispersing the light. The dispersed light is focused using transmission zone plates that are designed to match the dispersion of light in a broad wavelength range. Such a combination allows spectroscopy of plasma sources in one direction and imaging in the orthogonal direction.

We describe the design of the spectrometer covering 5 to 80 nm wavelength range with a spectral resolution of ~0.8 nm and a designed spatial resolution of ~10 um. We present the demonstration of the spectrometer with a laser produced plasma. We benchmark the spatial resolution of the spectrometer using wave propagation simulations. The qualitative agreement between the experimental results and the simulations verifies the demonstration of the device.

[1] Yahia Mostafa, Zoi Bouza, James Byers, Ievgeniia Babenko, Wim Ubachs, Oscar O. Versolato, and Muharrem Bayraktar, "Extreme ultraviolet broadband imaging spectrometer using dispersion-matched zone plates," Opt. Lett. 48, 4316-4319 (2023)

Presenting Author

Muharrem Bayraktar received his B.S. (2007) from Bilkent University in electrical and electronics engineering, his M.S. (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 applications such as adaptive EUV optics/wafer tables and metrology of EUV sources with novel spectroscopy techniques.

Spectral Characterization of EUV source at TNO

Aneta Stodólna[1], Jacqueline van Veldhoven[1], Peter van der Walle[1], Zoi Bouza[2], James Byers[2], Oscar Versolato[2], Muharrem Bayraktar[3]

[1] Unit High-Tech Industry of TNO, Delft, the Netherlands
[2] Advanced Research Center for Nanolithography, Amsterdam, the Netherlands
[3] Industrial Focus Group XUV Optics, University of Twente, Enschede, the Netherlands.

TNO exploits an EUV Beamline setup called EBL2, incorporating an Ushio laser-assisted discharge-produced (LDP) Sn source creating radiation around 13.5 nm (in-band). The setup is primarily used for studying and testing the interaction of EUV light with materials for EUV lithography applications, for which information about the full spectrum including in-band and out-of-band radiation is relevant.

Spectroscopic measurements were performed on EBL2 using a transmission grating spectrometer developed by Twente University and ARCNL. A complete spectrum in the range of 5.5-135 nm was obtained on a metrology port of the system to reconstruct the emission spectrum from the LDP source. The presentation will give an overview of the EBL2 setup and the used EUV spectrometer, describing how the spectroscopic measurements were performed and highlighting the results.

Presenting Author

Jacqueline van Veldhoven is a scientist at TNO. She acquired her PhD from the university of Nijmegen on the topic of molecular deceleration and trapping, after which she joined TNO to work on underwater acoustics and sea mine countermeasures. In 2013, she returned to the topic of chemical physics; her current research is within the field of nano-lithography with a particular interest in EUV, XPS and plasma.

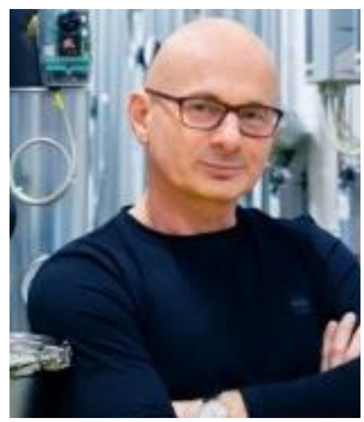
EUV collector mirrors for high-power LPP sources

Torsten Feigl

optiX fab GmbH

Presenting Author

Torsten Feigl is the CEO at optiX fab GmbH.



S85

Optical Constant Determination in the Vacuum-ultraviolet and EUV Spectral Ranges based on S - and P -polarized Reflectance Measurements

Frank Scholze, Najmeh Abbasirad, Richard Ciesielski, Alexander Gottwald, Michael Kolbe, Udo Kroth, Mattia Mulazzi, Qais Saadeh, and Victor Soltwisch

Physikalisch-Technische Bundesanstalt (PTB), Berlin, Germany

The introduction of EUV lithography into volume production of semiconductors initiated a big push for the development of short wavelength optical technologies in the whole vacuum UV (VUV) and EUV spectral for various applications. Those range from the support of EUV lithography (mitigation of so-called out-of-band radiation) to new metrology approaches using short wavelength radiation to improve the spatial resolution. The development of all those optical techniques requires the knowledge of respective materials optical constants in the respective spectral range. For most materials in this range, however, the optical constants are not precisely known because the corresponding measurements, particularly in the VUV range, are challenging for multiple reasons. We present recent advances of PTB in the determination of optical constants from spectral reflectance measurements for s- and p-polarized radiation using advanced statistical optimization techniques. We will particularly discuss the challenges for the VUV spectral range as compared to the EUV range.

Presenting Author

Frank Scholze studied physics at Technische Universität Dresden from 1982 to 1987 and received his Ph.D. in 1997 from TU Berlin. He is currently working on EUV and soft-x-ray detector calibration and optical component characterization, development of measurement methods for the characterization of components for EUV lithography, and x-ray scattering methods for the characterization of structured surfaces. He was the first Head of PTB’s Radiometry working group and in 2019 became the Head of the department Radiometry with Synchrotron Radiation.

S86

Lab-based EUV Spectroscopy: A Guide from Data Acquisition to Reconstructed Sample Parameters

Sven Glabisch[1], Sophia Schröder[1], Sascha Brose[1,2], Jochen Stollenwerk[1,2], and Carlo Holly[1,2]

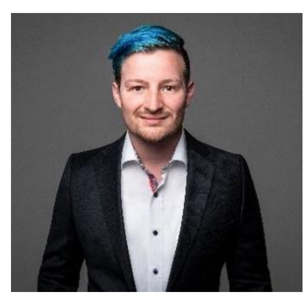
[1]RWTH Aachen University TOS - Chair for Technology of Optical Systems, Aachen, Germany
[2]Fraunhofer ILT - Institute for Laser Technology, Aachen, Germany

The continuous development in the semiconductor industry to ever-smaller nanostructures with an increased complexity raises the need to improve the metrology capabilities accordingly. Needs from the industry include the characterization of novel materials within the EUV spectral range as well as the characterization of deposition, etching, and lithographic processes. The Chair for Technology of Optical Systems at the RWTH Aachen University has realized a compact EUV spectrometer which utilizes a discharge-produced plasma (DPP) EUV source for a broadband and spectrally resolved reflectance measurements of samples under investigation. The non-destructive reflectance measurements for variable grazing incidence angles are the basis for the model-based reconstruction of the geometrical and material properties of thin-films as well as periodically structured samples under investigation with high accuracy. Since several optical components are placed within the optical beam path, a calibration measurement is required to compensate for the influence of these components.

In this presentation, the authors provide a detailed guide on the reconstruction of thin-film samples starting by the acquisition and processing of raw data and ending with the determination of uncertainties for reconstructed sample parameters including optical constants, surface properties and layer thicknesses. The involvement of supplementary data on the sample and the corresponding uncertainties are included within this reconstruction and provide the opportunity to combine the benefits of different measurement techniques.

Presenting Author

Sven Glabisch, M. Sc. (born 1994) studied physics at RWTH Aachen University and graduated 2021. Since the end of 2021, he is a Ph.D. student at RWTH-TOS and continues his studies in the field of laboratory EUV spectrometry, reflectometry and scatterometry with focus on model-based sample parameter reconstruction.



S91

Diffractive Neural Networks for Laser-beam Shaping – Principle and Applications

Paul Buske[1], Annika Völl[1],
Jochen Stollenwerk[1,2], and Carlo Holly[1,2]

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

Diffractive neural networks serve as a design methodology for arranging cascades of diffractive optical elements or spatial light modulators. This approach takes advantage of neural network training techniques by treating the optical elements as layers of an all-optical neural network. Prior studies have showcased the applicability of these systems in beam shaping tasks like combining beam splitting and shaping, optimizing the depth-of-focus using amplitude and phase as simultaneous optimization goals and creating 3D intensity distributions. Moreover, alignment errors can be rectified during training, and the method allows for the inclusion of other optical elements, like lenses, with ease. This presentation outlines the methodology, compares its benefits to alternative beam shaping techniques, and explores its applications in laser materials processing.

Presenting Author

Paul Buske is a PhD student at RWTH Aachen University. He received his bachelor's and master's degrees in physics, majoring in the subject of quantum field theory. Since 2019, he is working in the Computational Optics group at the Chair for Technology of Optical Systems. His research focuses on diffractive neural networks and their application in laser materials processing.

Research and Development of EUV Sources at Fraunhofer ILT

Klaus Bergmann

Fraunhofer Institute for Laser Technology ILT, Aachen, Germany

Since the mid 1980's Fraunhofer ILT and the related group at RWTH Aachen university is developing compact XUV sources. Initially, the focus was on discharge sources for x-ray microscopy in the water window and x-ray contact lithography at a wavelength of 1 nm. In 1997 it was possible to demonstrate the efficient, reliable and highly repetitive generation of EUV radiation at 13.5 nm from a pseudospark based gas discharge. After evaluation by the "Flying Circus" in 2000, Philips EUV invested in the power scaling of this system at the location of ILT in Aachen. At the same time AIXUV, a spin-off company ILT, commercialized this system for metrology applications. Nowadays, the AIXUV business is part of Research Instruments, who is providing sources and systems in the environment of EUV lithography. ILT has supported the activities of Philips and Xtreme technologies on light source development and the operation in the ASML's alpha demo- and the beta-tools. The talk will highlight some key events in this history and will shortly summarize the current and future activities on EUV sources and systems.

Presenting Author

Klaus Bergmann is the Group Manager for EUV Technology at the Fraunhofer Institute for Laser Technology - ILT in Aachen, Germany. The focus of work is on the scaling of plasma based EUV- and soft x-ray sources and their applications in future structuring and analysis methods. Klaus Bergmann received the M.S. degree in physics and the PhD degree from the University of Technology, RWTH Aachen, Germany, in 1992 and 1996, respectively. Since 1992, he has been with the Department for Plasma Technology at the Fraunhofer Institute for Laser Technology – ILT with main focus on XUV source and system development.

S93

EUV technology for at-wavelength characterization tasks

Sascha Brose[1,2], Sophia Schröder[1], Bernhard Lüttgenau[1], Sven Glabisch[1], Ismael Gisch[1], Adelind Elshani[1], Lars Lohmann[1], Linus Nagel[1], Jochen Stollenwerk[1,2], and Carlo Holly[1,2]

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

In the realm of the industrial developments of applying extreme ultraviolet radiation for the structure definition of integrated circuits there is a strong demand for characterization techniques of materials and nanostructures using EUV radiation. These tasks include the determination of optical constants, nanoscale structure dimensions, photoresist performance or material lifetime studies.
The EUV Technology group at RWTH Aachen University addresses those tasks by utilizing EUV radiation provided by a discharge-produced plasma, a source concept mainly developed and commercialized by Fraunhofer ILT and their research partners. The emission properties of the sources, like their intense broadband EUV emission and partially coherence, require suited experimental approaches that are designed to benefit from it. Realized experimental setups for the investigation of industrial to fundamental research tasks include EUV reflectometry, interference lithography, high-intensity exposures and the corresponding simulation or modelling framework. In this presentation the core competencies and research fields of the EUV Technology group are presented in short with references to the corresponding presentations within the main program.

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 an expert in micro- and nanofabrication processes of optical components especially designed for EUV wavelengths. He has authored and co-authored more than 37 scientific publications mainly in the field of EUV lithography and metrology.

S94

Computational Optics for the Design of Cutting-edge Optical Components and Systems

Annika Völl[1], Jacqueline Dahlmanns[1], Thomas Bussek[1], Marvin Schossau[1], Paul Buske[1], Jochen Stollenwerk[1,2], and Carlo Holly[1,2]

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

In recent years, photonic applications such as laser material processing and illumination have become increasingly demanding in terms of complex and efficient beam shaping. As a result, completely new optical concepts are required. The efficient and precise design of these innovative optical elements is only possible with computer-based models and simulations, which provide an economical, easy, and fast insight into their functionality and design freedom.

At RWTH-TOS, we develop several numerical methods for the design of cutting-edge optical components and systems with a strong focus on industrial applications. Among these are algorithms for the design of non-imaging freeform optics and diffractive neural networks for complex beam shaping, for the derivation of application specific intensity distributions in laser materials processing as well as for the multi-physical simulation of diode lasers for high-power applications and quantum technology. This talk will give a overview of recent and current research activities at the Computational Optics group at RWTH-TOS and show some potential application areas.

Presenting Author

Annika Völl holds a M.Sc. degree in Physics from RWTH Aachen University and was awarded a Ph.D. in 2020 for the research on application-adapted beam shaping in laser materials processing. Currently, she works as a Junior Group Leader for Computational Optics at the Chair for Technology of Optical Systems TOS at RWTH Aachen University. Her research interests lie in the development of application-oriented numerical methods for optics and laser technology.

Optical Systems for High-performance, Individual (laser) Applications

Marcel Prochnau[1], Cailing Fu[1], Nicole Grubert[1], Mario Hesker[1], Jörg Hofmann[1], Oskar Hofmann[1], Robin Kurth[1], Benedikt Schober[1], Jochen Stollenwerk[1,2], and Carlo Holly[1,2]

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

Modern optical systems often include close interaction of optical, mechanical and electronic components. Dynamic adaptation to changing environmental conditions, variable intensity distributions needed in laser applications, compensation of optical deviations as well as adaptation to processes are requirements that are expected from today's optical systems.

At TOS our research focus is on optical systems for high-power laser applications with application-adapted intensity distributions up to the multi-kW range. In addition to beam shaping, the simulation and compensation of thermo-optical effects is a major focus. To increase process efficiency, especially in the field of ultrashort pulse processing, we are developing systems for multi-beam processing with individually manipulable beams.

To simplify and accelerate the currently very time-consuming design process of optical systems, we are investigating the use of AI for the automated design of optical systems. For the automated monitoring of optical systems and the prediction of maintenance cycles we are developing a digital optical twin.
This talk will give a short overview of recent and ongoing research activities at the Optical Systems Group at RWTH-TOS and show potential application areas.

Presenting Author

Marcel Prochnau holds a Dipl.-Ing. degree in Mechanical Engineering from RWTH Aachen University and received his Ph.D. in 2020 for his research on the integration of Industry 4.0 in the context of the assembly of optical systems. Currently, he works as a group Leader for the group "Optical Systems" at the Chair for Technology of Optical Systems TOS at RWTH Aachen University.

High-throughput Micro-Machining Using Ultrashort Pulsed Lasers

Martin Osbild

Fraunhofer ILT - Institute for Laser Technology, Aachen, Germany

Laser micromachining using ultrashort pulses (USP) of around 1 ps offers excellent ablation quality meeting most roughness requirements of various industries. Nevertheless, the industrial adoption of USP laser microstructuring is often impeded by its limited productivity, primarily due to the constrained usable fluence (pulse energy per unit area) required to maintain acceptable quality. However, several approaches can address this issue, such as fast beam deflection, burst processing, or multibeam processing. This presentation focuses on the latter, showcasing both static and flexible multibeam processing strategies.

Static multibeam processing involves the simultaneous utilization of multiple laser beams, guided over the workpiece using a galvo scanner. This technique enhances material removal rates while upholding high precision, making it well-suited for applications with periodic structures, where speed and quality are critical, such as battery production. In contrast, flexible multibeam processing involves the individual modulation of all partial beams. This level of flexibility allows for the creation of arbitrary, non-periodic surface structures, significantly expanding the applicability of USP laser micromachining within industrial sectors, such as toolmaking. By presenting these innovative approaches, we aim to demonstrate how scalable solutions can overcome the productivity challenges associated with USP laser micromachining, ultimately opening up new possibilities for its widespread industrial implementation.

Presenting Author

Martin Osbild is a team leader within the group "Micro- and Nanostructuring" at the Fraunhofer Institute for Laser Technology (ILT) in Aachen, Germany. Holding an academic background in mechanical engineering, his work revolves around ultrashort pulse laser applications, encompassing microdrilling, surface structuring, and USP polishing. Currently, he develops both ultra-fine and ultra-productive laser ablation processes using innovative beam shaping.

Laser-Based Manufacturing of Glass Optics

Manuel Jung, Edgar Willenborg

Fraunhofer ILT - Institute for Laser Technology, Aachen, Germany

The production of optics from glass requires highest precision and reliability. Since the times of Joseph von Fraunhofer around 200 years ago, the machines for processing optical surfaces have become larger and several orders of magnitude more precise and are now running highly automated, but the process principle has remained the same: Grinding with an indeterminate cutting edge followed by polishing with loose grit is used to ablate the glass material into shape and gloss. A new approach is laser-based optics manufacturing. Laser radiation can be used to produce shapes, polish surfaces and correct shape errors. The potential of the laser processes for optics manufacturing lies primarily in the production of non-spherical optics, since in laser processing the processing times and achieved surface qualities are mostly independent of the shape of the optics. The lecture will give an overview of the different laser processes and their status for optics manufacturing.

Presenting Author

Manuel Jung finished his studies in industrial engineering at RWTH Aachen University in 2018. Since then he has been working at Fraunhofer ILT in the laser polishing group. His main topic is laser polishing of glass for optical applications.

S98

Laser-based Additive Manufacturing of Components for Extreme- environments

Tim Lantzsch[1]

[1]*Fraunhofer - Institute for Laser Technology ILT, Aachen, Germany*

In recent years, additive manufacturing (AM) techniques such as Laser Powder Bed Fusion (LPBF) have become a viable option for production of highly complex components without additional tools. Especially the combination of application relevant materials with complex geometrical features such as internal cooling channels enables the manufacturing of components for extreme environments via laser-based AM. Nevertheless, the use of high-performance materials is currently limited by a lack of part quality and process robustness. The enhancement of process boundaries and material rage is thus crucial for a wider industrial use of laser-based AM. Fraunhofer ILT utilizes a combined processes and systems engineering approach to address these challenges. Current research topics include multi-material AM, novel machine concepts as well as adaptive process control and material qualification.

Presenting Author

MarTim Lantzsch is head of Laser Powder Bed Fusion department at Fraunhofer-Institute for Laser Technology ILT. He obtained his degree in Industrial Engineering from RWTH Aachen University. Since joining Fraunhofer ILT in 2018, Tim has been working in different positions in the field of laser-based additive manufacturing. Furthermore, he is a PhD candidate at RWTH Aachen University. His research focuses on novel laser beam sources and optical systems for highly productive LPBF machines.

Laser Material Deposition for Coating, Repair and Additive Manufacturing

Thomas Schopphoven

Fraunhofer Institute for Laser Technology ILT, Aachen, Germany

At the Fraunhofer Institute for Laser Technology ILT, Laser Material Deposition (LMD) has been intensively researched and systematically developed for a wide range of applications and industries for more than 35 years. With LMD, metal layers with thicknesses between 0.01 mm and 2 mm can be applied with high precision to almost any metallic material in a very short time. By overlapping several deposited tracks, two-dimensional coatings, for example for wear and corrosion protection or functional coatings, can be produced. If several layers are deposited on top of each other, the process can also be used for additive manufacturing including processes for repair applications and individualization of prefabricated parts (hybrid AM). Due to the precisely controllable energy input, components and alloys that are generally considered difficult to weld can be processed. The easy adaptability and flexibility for different fields of application (coating, repair and additive manufacturing) and its simple integrability into existing process chains make the process particularly attractive for various different industries and applications.

Presenting Author

Dr.-Ing. Thomas Schopphoven is head of the "Laser Material Deposition" department at the Fraunhofer Institute for Laser Technology ILT in Aachen. After graduating in mechanical engineering from RWTH Aachen University in 2012, he spent the following years developing the Extreme High-speed Laser Material Deposition process (EHLA) from an idea to an industrial production process. In 2019, he completed his doctorate with distinction at RWTH Aachen University on the process fundamentals of EHLA.

Mitigation of Polarization-dependent Uncertainties in a Compact EUV Spectrometer

Sophia Schröder[1], Sven Glabisch[1], Sascha Brose[1,2], Jochen Stollenwerk[1,2], and Carlo Holly[1,2]

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

The need for non-destructive, optical metrology for nanostructures and materials with growing demands on sensitivity to ever-smaller features pushes the development of metrology techniques like EUV and X-ray reflectometry and scatterometry. At RWTH Aachen University a setup was realized that uses EUV radiation from discharge-produced plasma (DPP) EUV sources to allow high precision EUV metrology in a compact setup. The radiation from the DPP EUV source is initially unpolarized, but reflections off any surface in the setup including diffraction gratings, deflection mirrors, and the sample itself introduce a partly polarization to the probing radiation. This change in polarization is only partly accounted for in the calibration of the setup but contributes to the measurement uncertainty on the measured reflectance.

In this presentation, the influence of polarization on the measured reflectance and uncertainty is determined with respect to incidence angle and wavelength. Additionally, a calibration strategy is introduced which allows to separate the polarization effect of the metrology setup from the polarization introduced by the sample itself. This reduces the measurement uncertainties due to polarization and allows to reconstruct the sample dependent polarization as an additional sample parameter in addition to e.g., optical constants, layer thicknesses and, surface structures.

Presenting Author

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

Multi-level Phase-shifting Mask Concept for EUV Interference Lithography

Lars Lohmann[1], Bernhard Lüttgenau[1], Sascha Brose[1,2], Serhiy Danylyuk[2], Jochen Stollenwerk[1,2], and Carlo Holly[1,2]

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

The fast and reliable fabrication of complex periodic nanostructures with feature sizes below 100 nm is essential for numerous industrial and scientific applications. A compact nanopatterning tool using a discharge-produced plasma (DPP) EUV radiation source has been developed at RWTH Aachen University enabling fast and accessible nanopatterning with either 10.9 nm or 13.5 nm irradiation wavelength. For partially coherent radiation as provided by the DPP EUV source, the (achromatic) Talbot lithography is applied with a demonstrated resolution in the sub-30 nm regime and a theoretical resolution limit below 10 nm for optimized phase-shifting masks. For the realization of efficient phase-shifting transmission masks, various material combinations and geometries can be applied resulting in a maximized aerial image contrast in the wafer plane.
In this contribution, the authors investigate the use of highly efficient metal-based phase-shifting transmission masks to move closer towards the theoretical resolution limit for periodic nanopatterning. To further increase the pattern quality and extend the possible pattern geometries to complex periodic and even arbitrary patterns, the design and fabrication process of multi-level phase-shifting masks using several subsequent etching steps is considered. The design of the layer system and a selection of suitable dry etch chemistries that provide high selectivity are presented along with first experimental etch process results.

Presenting Author

Lars Lohmann is a PhD student at RWTH Aachen University. He received his bachelor's and master's degrees in chemistry, majoring in the subject of magnetic resonance spectroscopy. Since 2023, he is working in the EUV technology group at the Chair for Technology of Optical Systems. His research topics include EUV interference lithography with compact EUV sources and related process technologies.

S112

Development of an Ultra-compact Inline Transmission - grating Spectrograph for EUV Wavelengths

Sascha Brose[1,2], Serhiy Danylyuk[2], Bernhard Lüttgenau[1], Ismael Gisch[1], Lars Lohmann[1], Jochen Stollenwerk[1,2], and Carlo Holly[1,2]

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

In this contribution the design, realization, and characterization of a transmission grating spectrograph (TGS) for spectral characterization and monitoring tasks at EUV wavelengths is presented. The overall dimensions of the EUV-TGS have been minimized to allow for simple integration in existing beamlines and setups while maintaining sub-Angstrom spectral resolution. The main module (length = 70 mm) 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 design and measurement performance of the EUV-TGS are presented, demonstrating that this ultra-compact spectrograph can be easily introduced into EUV setups that will benefit from an inline diagnostic option.

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 37 scientific publications mainly in the field of EUV lithography and metrology.

S113

Vaporization Dynamics of Liquid Tin-sheet Targets

Authors: H.K. Schubert, D.J. Engels, R.A. Meijer, B. Liu, O. O. Versolato

ARCNL, Amsterdam, The Netherlands

In state-of-the-art nanolithography machines, tin-droplet laser-produced plasma is the source of extreme ultraviolet (EUV) light. In those machines, tin droplets are shaped into target sheets to optimize the EUV light generation, a process called 'target shaping'. Even larger gains could be achieved with 'advanced target shaping'. Inspired by this concept, we investigate the vaporization of a free-standing tin sheet.

Experimentally, we vaporize liquid tin sheet using a 100 ns box pulse while varying its intensity around 10^7 W/cm2. We resolve the vaporization process using 5ns-time-resolved and 5um-resolution shadowgraphs. We employ two different methods to investigate the vaporization for sheet thicknesses ranging 20–200 nm. The experimental data conclusively shows that the sheet thins gradually during the vaporization. Also, the rate of vaporization depends linearly on the intensity of the laser pulse.

A model for heat transport and vaporization is developed. The model can accurately predict the vaporization with only the initial sheet thickness and the laser intensity as input. The new insights on the gradual thinning and the rate of vaporization could be applied to produce targets optimally suited to produce EUV light.

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 shaping of liquid tin with laser pulses.

S114

TEUS: High-brightness EUV LPP Light Source based on Fast-rotating Target: Product Overview and Specifications.

Alexander Tovstopyat, Mikhail Krivokorytov, 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

We present performance metrics for the commercially available TEUS product line. TEUS-S is a high-brightness EUV LPP light source based on a fast rotating liquid metal target with EUV collection angle of 0.05sr. The TEUS-S100 and S400 models employing 100W and 400W of average laser power respectively have been characterized with particular attention to the collector optics lifetime. It is estimated that 10% mirror reflectivity degradation will occur after 2 years for the TEUS-S100 and after 6 months for the TEUS-S400 in 24/7operation mode.
The TEUS-S400 source provides more than 30 mW of in-band (±1%) EUV radiation after the debris mitigation system.
In this report, we will focus on measurements of source size, position stability as well as optics lifetime studies. In addition, we will describe customer use cases for TEUS and show where available source performance at the customer site.

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.

S115

Sinusoidal Transmission Grating Spectrometer for EUV Measurement

Noa Kliss

L2X Labs, Jerusalem, Israel

Spectral measurements play a vital role in understanding laser-plasma interactions. The ability to accurately measure the spectrum of radiation sources is crucial for unraveling the underlying physics. In this article, we introduce a novel approach that significantly enhances the efficiency of binary Sinusoidal Transmission Grating Spectrometers (STGS). The grating was optimized specifically for Extreme Ultraviolet (EUV) measurements. The new design, High Contrast Sinusoidal Transmission Grating (HCSTG), not only suppresses high diffraction orders and retains the advantageous properties of previous designs but also exhibits a four-fold improvement in efficiency of transmission into first order. In addition, the HCSTG offers exceptional purity in the first order due to effectively eliminating half-order contributions from the diffraction pattern. The HCSTG spectrometer was employed to measure the emission of laser-produced Sn plasma in the 1-50 nm spectral range, achieving spectral resolution of $\lambda/\Delta\lambda=60$. The diffraction patterns from different STGs are analyzed, highlighting the advantages offered by the HCSTG design. This novel, efficiency-enhanced, HCSTG spectrometer opens up new possibilities for accurate and sensitive EUV spectral measurements.

Presenting Author

Noa Kliss is a M.Sc. student in the Racah Institute of Physics, the Hebrew University of Jerusalem, Israel, working under the supervision of Prof. Aerie Zigler. She is also a researcher in L2X Labs, working on advances approaches for laser-plasma interaction in laser-produced Sn plasma for EUV sources. She received her B.Sc. in physics from the Hebrew University of Jerusalem, Israel.

S116

3D Printed Zone plate Optics for Soft X-rays

Eoin Byrne

UCD

The research is based on 3D printed Zoneplate Optics for laser plasma produced soft x-rays using a nanoscribe.The poster details some of the developments from the earlier stages of the research to the current system used to get a functional optic for experimentation. With the aim of testing their effectiveness and efficiency compared to commercially produced zoneplates from e-beam lithography. The processes developed have made it possible to prototype zoneplate optics quicker and far cheaper than commercially available options.

Presenting Author

Eoin Byrne is a student in the field of physics with a degree in Physics with Medical Physics and Bioengineering from Technological University Dublin. He is currently studying at University College Dublin completing his research masters in 3D printed Optics for soft X-rays from laser produced plasmas in the Spectroscopy group of the Physics Department.

Ultrabroadband EUV Inspection with High-harmonic Generation Sources

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

[1] Indigo Optical Systems GmbH, Jena, Germany
[2] Institute of Optics and Quantum Electronics, Jena, Germany
[3] Helmholtz Institute Jena, Jena, Germany
[4] Laserinstitut Hochschule Mittweida, Mittweida, Germany

We present a novel imaging method using broadband EUV light that enables non-destructive 3D cross-sectional imaging with nanometer resolution, material sensitivity, and EUV reflectometry [1,2]. We call this method extreme ultraviolet coherence tomography (XCT), which is partially based on the Fourier-domain optical coherence tomography (OCT). With our laboratory setup, using a laser-driven source to generate high harmonics [3], we achieve nanoscale axial resolution for a single buried layer [4]. Moreover, with XCT we are able to reconstruct the structure of the sample, the absolute values of spectral reflectance across layers, its phase, and local details of material composition, such as monolayers of graphene [5,6]. The technique and the use of the broadband EUV source we developed allows us to study samples down to 180 eV, making it suitable for the study of various semiconductor materials and structures. At Indigo, we are taking our imaging technology to higher TRLs, capitalizing on both the technology and its individual components.

[1] Fuchs et al., Scientific Reports 6, 20658 (2016)
[2] Fuchs et al., Applied Physics B, 106, 789-795 (2012)
[3] Wünsche et al., Optics Express, 25(6), 6936-6944 (2017)
[4] Fuchs et al., Optica, 4(8), 903-906 (2017)
[5] Wiesner et al., Optica, 8(2), 230-238 (2021)
Wiesner et al., Optics Express, 30(18), 32267-32279 (2022)

Presenting Author

Martin Wünsche received his PhD in 2020 at the University of Jena, Germany. During his PhD work in the group of Prof. Gerhard Paulus he developed a laser-based XCT setup, which is the basis for the investigation of layered nanostructured samples. He is co-founder and CEO of Indigo Optical Systems GmbH, a spin-off of the University of Jena, which develops high-resolution EUV spectrometers and beamlines and performs EUV measurements of layered nanostructures relevant for EUV lithography.