Workshop Abstracts

EUV Litho, Inc.

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Vivek Bakshi (EUV Litho, Inc.), Chair

Oscar Versolato (ARCNL), Co-Chair

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Abstracts

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S2

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

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

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Gigaphoton develops CO_2 Sn LPP EUV light source which is the most promising solution as the 13.5nm high power light source for HVM EUVL [1]). Unique and original technologies including combination of pulsed CO_2 laser and Sn droplets, dual wavelength laser pulses for shooting and debris mitigation by magnetic field have been applied. We have developed first practical source for HVM "GL200E" in 2014[3]). Then it was demonstrated with high average power CO_2 laser more than 20 kW at output power in cooperation with Mitsubishi Electric[2]). Pilot#1 is up and running and it demonstrates the HVM capability; EUV power recorded at 111 W on average (117 W in burst stabilized, 95% duty cycle) with 5% conversion efficiency for 22-hour operation in October 2016[3]). Availability is achievable at 89% (2 weeks average), also superior magnetic mitigation has demonstrated promising mirror degradation rate (= 0.5%/Gp) at 100W or higher power operation with dummy mirror test. We have demonstrated >300 W operation data (short-term) and actual collector mirror reflectivity degradation rate is less than 0.15%/Gp by using real collector mirror around 125 W (clean power at intermediate focus) in burst power > 10 billion pulses operation[4]). Also, we will update latest challenges for >250W average long-term operation with collector mirror at the conference[5]). Next requirement for high-NA exposure tool is >800 W. The feasibility of CO2 laser driver is discussed.

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4) Hakaru Mizoguchi et al.:" Challenge of >300W high power LPP-EUV source with long collector mirror lifetime for semiconductor HVM", Proc. SPIE 11323, Extreme Ultraviolet (EUV) Lithography XI (2019) [11323-28]
5) Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Hiroshi Tanak, Yukio Watanabe, Tsukasa Hori, Yutaka Shiraishi, Tatsuya Yanagida, George Sumangne, Tsuyoshi Yamada, Takashi Saitou:" Challenge of >300W high power LPP-EUV source with long mirror lifetime-III for semiconductor HVM",Proc. SPIE. 11609, Extreme Ultraviolet (EUV) Lithography XII (2021)

Presenting Author

Dr. Hakaru Mizoguchi is a Senior Fellow in Gigaphoton Inc., and Fellow member of The International Society of Optical Engineering (SPIE). He joined CO_2 laser development program in Komatsu for 6 years since 1982. He was a guest scientist of Max-Plank Institute Bio-Physikalish-Chemie in Goettingen in Germany from 1988 to 1990. Since 1990 he concentrated on KrF, ArF excimer laser and F2 laser development for lithography application. He was one of the founders of Gigaphoton Inc. From 2002 to 2010 he organized EUV research group in EUVA program. Now he is promoting EUV light source product development up to now. He got Sakurai award from OITDA Japan in 2018. He got IAAM Scientist Award in 2020. He is also a guest professor in Kyushu university since 2021.

S3

Fundamental Studies of EUV Lithography Including Shorter Wavelength at NewSUBARU Synchrotron Light Facility (Keynote)

Takeo Watanabe

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EUV lithography started to employ as manufacturing (HVM) technology of 7-nm-node-logic devices for smart phones from 2019, and it started to use in HVM of 5-nm-node logic devices in 2020. However, it still has critical issues toward HVM in 5-nm node and beyond.

From 1995, the research and development (R&D) program of EUV lithography started at NewSUBARU [1] synchrotron light facility of Laboratory of Advanced Science and Technology for Industry (LASTI), Himeji Institute of Technology (present University of Hyogo). The first collaboration work started between HIT, Nikon, and Hitachi Central Research Lab. in 1996 to develop full exposure EUV tool which was called "ETS-1". Using this tool, 60 nm L/S pattern replication is demonstrated in a large area size. After that, ASET program, four national project such as Selete, EUVA, and EIDEC were carried out in Japan, and each project period was five years. In these programs, the fundamental R&D of EUV resist, EUV mask, EUV optics, and EUV light source were carried out at NewSUBARU, LASTI. And we involved in these three projects for the R&D of EUV resist, EUV mask, and EUV optics. And we also have collaborated with many private companies, universities, and research institutes in the world.

The key points of R&D activities of EUV resist, EUV mask, and EUV optics are introduced. In addition, it is discussed that the lithographic potential extension of EUVL to shorter exposure wavelength.

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Presenting Author

Takeo Watanabe received his Ph.D. from Osaka City University in 1990. He is a Full Professor, Director of Center for EUV, and Dean of Laboratory of Advanced Science and Technology for Industry, University of Hyogo. He is an expert of the EUV lithographic technology, including optics, exposure tool, mask and resist related technologies. He has authored over 250 technical papers, and he is international affair, and the organizing and program committee members, of the International Conference of Photopolymer Science and Technology (ICPST). He is also Conference Chair of the International Conference of Photomask Japan. And he is a program committee member of the International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication (EIPBN).

S4

Attosecond Quantum Technologies for Extracting the Structural, Mechanical, and Transport Properties of Nanostructured Materials (Keynote)

Margaret M. Murnane

JILA and STROBE, University of Colorado Boulder, Boulder, CO 80309-0440

High harmonic quantum light sources provide an exquisite ability to harness and control short wavelength light, with unprecedented control over the spectral, temporal, polarization and orbital angular momentum of the emitted waveforms. These represent the most-complex coherent electromagnetic fields ever created, controlled on sub-Å spatial scales and sub-attosecond temporal scales, from the UV to the keV photon energy region. These advances are providing powerful new tools for near-perfect x-ray imaging, for coherently manipulating quantum materials using light, and for designing more efficient nanoscale devices.

This talk will also discuss how ultrafast, coherent extreme ultraviolet (EUV) sources uncovered surprising new behavior in 2D, magnetic and nanostructured systems. Counterintuitively we found that the thermal dissipation efficiency increases as nanoscale heat sources are packed more closely together. Combined with advanced theory, this new understanding can help with better thermal management in nano- and quantum technologies, including the development of advanced nanoelectronics and efficient thermoelectric devices.

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Presenting Author

Margaret is a Fellow of JILA and a Distinguished Professor at the University of Colorado. She runs a joint, multi-disciplinary, research group with her husband, Prof. Henry Kapteyn. She received her B.S and M.S. degrees from University College Cork, Ireland, and her Ph.D. degree from UC Berkeley. Margaret, with her group and collaborators, uses coherent beams of laser, EUV and x-ray light to capture and manipulate the structure and interactions in materials at the nanoscale.

She is a Fellow of the American Physical Society, and the AAAS, and a member of the National Academy of Sciences and the American Philosophical Society. In 2021, she and Kapteyn shared the Benjamin Franklin Medal in Physics. Margaret is the Director of the National Science Foundation STROBE Center, where a consortium of 6 universities are building the microscopes of tomorrow.

S20

A Community Platform for Just Atomic Computations

Stephan Fritzsche

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Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität, Jena, 07743, Germany

Electronic structure calculations of atoms and ions have a long tradition in physics with applications in basic research and the development of novel light sources. With the Jena Atomic Calculator (JAC), I shall present a new implementation of a (relativistic) structure code for the computation of atomic amplitudes, properties as well as a large number of excitation and decay processes for open-shell atoms and ions across the periodic table. JAC [1,2] is based on Julia, a new programming language for scientific computing, and provides an easy-to-use but powerful platform to extent atomic theory towards new applications.

References

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[2] Fritzsche, User Guide & Compendium to JAC (unpublished, 2019).

Presenting Author

Stephan Fritzsche received his Ph.D. (with focus on relativistic atomic structure theory) in 1992. After post-doc and research positions in Oxford, Gothenborg, Kassel, Heidelberg, Darmstadt as well as Oulu, he now holds a chair in theoretical physics at Jena. His research topics include electronic structure theory, light-matter interactions in intense fields as well as the modeling of a wide range of atomic processes.

S26

Numerical Model of Hybrid Laser-heated Discharge Plasma Devices for EUV Metrology (Invited)

V. Sizyuk[1], F. Melsheimer[2,3], L. Juschkin[2], K. Tsigutkin[2], T. Sizyuk[4], A. Hassanein[1]

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[3] *RWTH Aachen University, Aachen, 52056, GER*
[4] *Argonne National Lab, Lemont, IL 60439, USA*

Discharge and laser produced plasma (DLPP) devices are being introduced as a light source for Extreme Ultraviolet (EUV) generation. To simulate the environment of hybrid DLPP device, we have developed an integrated comprehensive computer package HEIGHTS-DLPP. The package combines simulations of two plasma models (DPP & LPP) and addresses a set of integrated self-consistent processes: external laser energy input and plasma energy balance, plasma resistive magnetohydrodynamics, plasma heat conduction, detailed radiation transport (RT), and laser radiation absorption and refraction. We simulated and optimized DLPP devices using Xe as a working media. The full 3D Monte Carlo scheme was integrated for the RT and EUV output calculations in Xe using more than 3600 spectral groups. The modeling results are compared to a laser heated discharge plasma (LHDP) experiments conducted at Forschungszentrum Jülich which was presented at the 2019 Source Workshop. Experimental layout and modeling conditions are matched carefully, and results of simulation and experiment are in good agreement. Theoretical models, developed and integrated in HEIGHTS package, showed wide capabilities and flexibility. The models and package can be used for optimization of experimental settings, investigation of DLPP devices with complex design, analyzing the impact of integrated spatial effects and precise timeline sequences on the final EUV output, EUV source size, shape, and angular distribution.

Presenting Author

Valeryi Sizyuk received Ph.D. degree in 1997 from Byelorussian State University in Minsk, Belarus. He is a member of HEIGHTS team from 2002 working at Argonne National Lab. Since 2013 he is Research Associate Professor of Nuclear Engineering at Purdue University, IN. He has more than 20 years of experience in plasma science, atomic and nuclear physics, computational physics, and development of the software for plasma material interactions. V. Sizyuk is the main developer of the HEIGHTS package for the modeling of laser and discharge produced plasma and fusion reactor environment.

S32

cERL IR-FEL as PoC of EUV and Blue-X FELs for Future Lithography (Invited)

Norio Nakamura, Ryukou Kato, Hiroshi Sakai, Kimichika Tsuchiya, Yasunori Tanimoto, Yosuke Honda, Tsukasa Miyajima, Miho Shimada, Takashi Obina, Hiroshi Kawata

High Energy Accelerator Research Organization (KEK)

Development of a high-power EUV light source is still very important for overcoming stochastic effects with a high throughput. The required EUV power to realize the 3-nm node and beyond is estimated to be more than 1 kW [1]. An ERL-based EUV-FEL for lithography was designed and studied to provide more than 1-kW EUV power for multiple scanners [2]. In the next step, an ERL-based FEL should be really demonstrated as proof of concept (PoC) of EUV and Blue-X FELs for future lithography. Fortunately, an infrared (IR)-FEL project at the Compact ERL (cERL) started as a part of a NEDO project for the purpose of developing high-power IR lasers for high-efficiency laser processing [3]. The IR-FEL construction was completed in May 2020 and the commissioning was performed in June to July 2020 and in February to March 2021. In this presentation, we will briefly review the EUV-FEL and present construction and commissioning of the cERL IR-FEL including future work.

References

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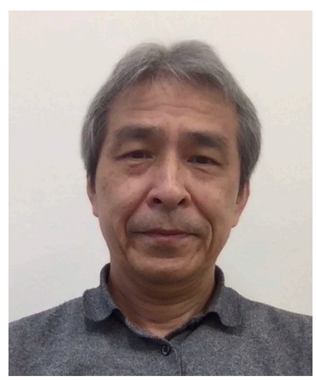
Presenting Author

Norio Nakamura is a professor and a leader of the beam dynamics and magnet group in Accelerator Division VI (light source division) of the Accelerator Laboratory at High Energy Accelerator Research Organization (KEK). He received his Ph. D in Physics from the University of Tokyo in 1987. He worked for the Photon Factory at KEK from 1987 to 1996 and then for the Synchrotron Radiation Laboratory of the Institute for Solid State Physics at the University of Tokyo from 1996 to 2011. He is studying advanced light sources based on accelerators including energy-recovery linac (ERL)-based FELs and next-generation synchrotron radiation sources.



S33

Solid State Tm:YLF Lasers for Driving EUV Sources (Invited)

Brendan A. Reagan, Justin Galbraith Thomas Galvin, Glenn Huete, Hansel Neurath, Craig Siders, Emily Sistrunk, Thomas Spinka, and Issa Tamer

Lawrence Livermore National Laboratory

Diode-pumped, solid-state lasers operating at wavelengths near 2 μm are potential future drivers of extreme ultraviolet sources for lithography. The Big Aperture Thulium (BAT) laser concept, based on gas-cooled, directly-diode pumped Tm:YLF, represents a viable path towards the production of Joule-level pulses at tens-hundreds of kilowatts average power. Recent experimental results including the demonstration of a compact diode-pumped Tm:YLF amplifier that produces Joule-level pulse energies with nanosecond duration will be presented. These results combined with modelling efforts aimed at optimizing a Tm:YLF-based system for driving future EUV sources will be discussed.

Presenting Author

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

S34

Development of SSMB EUV Light Source at Tsinghua University (Invited)

Chuanxiang Tang
On behalf of the Tsinghua SSMB group

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Steady-state microbunching (SSMB) is an electron storage ring-based scheme which promises high-average-power and narrow-band EUV radiation. A compact SSMB EUV source is a cost-effective candidate to serve the high-volume manufacturing of EUV lithography. The mechanism of SSMB has been recently experimentally demonstrated (Nature 590, 576–579(2021)). In this talk, we present the design progress of SSMB EUV light source at Tsinghua University, which includes the main physics problems and key technologies we need to overcome, and the properties of the EUV light it is designed to provide.

Presenting Author

Chuanxiang Tang is a Professor in Tsinghua University, Beijing, China. He got his PhD degree at Tsinghua University in 1996. And began his teaching and researching career in the same university at the same time. He worked at DESY during 1996 to 1998 as a visiting scholar.
His research areas include low energy electron linacs and their applications in industrial imaging, photocathode rf gun, high brightness electron beam and its applications in MeV electron diffraction, Inverse Compton scattering x/gamma ray source, free electron laser and other novel light sources. He is focusing on steady state microbunching (SSMB) light source studies these years and leading the SSMB group in Tsinghua University.

S35

Laser Plasma Characterization Techniques and Results from UCD (Invited)

Fergal O'Reilly, Padraig Dunne, Mateusz Olszewski

School of Physics, University College Dublin

Laser plasmas are versatile sources of ions and photons, that give us a window into highly charged dense plasmas which have been studied for over 50 years. Soft x-ray imaging and spectroscopy of these plasmas is challenging because of the short absorption lengths of these photons, which requires experiments to be done in vacuum, and because of the high cost of vacuum components such as detectors, filters and vacuum motion apparatus. In UCD we have been developing low-cost solutions to some of these problems to allow us to build more versatile experiments, and in this talk we will share some of our experiences with these tools and give an update on some results from the Group.

Presenting Author

Fergal O'Reilly is a researcher in UCD School of Physics. He received his PhD in Atomic Spectroscopy from UCD in 1998. His research activities have focused on EUV and soft x-ray spectroscopy of laser-produced plasmas, ionic photoabsorption, and EUV/soft x-ray source, optics and microscope development.

S1

EUV Multilayers Mirrors – Wider, Thinner and Deeper (Keynote)

Marcelo Ackermann

University of Twente
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The state-of-the-art Mo-Si multilayer mirrors (MLM) used for EUV optics are moving ever so close to their theoretical limits. Interface engineering, the atomic-level control of what happens at the edge between two layers of MLMs, has allowed achieving reflectivities of more than 70% at 13.5nm and over 65% for 6.6 nm wavelengths. However, these MLMs still have some physical limitations in terms of angular and energy bandwidth. In this presentation we show both designs and actual mirrors that can overcome these limitations, including analysis of where layer and interface properties become critical for mirrors. To reach far beyond EUV, we also show applications of MLM's all the way to the soft X-ray range, and confirm that even there, the atomistic interface engineering is still key to understand and achieve high reflectivities.

Presenting Author

Marcelo Ackermann is chair of the Industry Focus Group – X-ray and EUV (XUV) optics at the MESA+ institute of 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 J.W.M Frenken and Prof. S. Ferrer. After that held different leading positions in industrial research for the development of X-ray, visible and IR optics for companies like cosine Research, Helbling Technik, SCHOTT Advanced Optics and ASML. In 2020 he re-joined academic research as full professor in the XUV optics group, focussing on the development of next generation reflective, refractive and transparent X-ray and EUV optics in collaboration with industrial partners like Zeiss SMT, ASML and Malvern Panalytical.

S36

Laser-produced Plasma EUV Sources for 13.5 nm and Beyond (Invited)

Takeshi Higashiguchi[1]

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

We show the laser-produced plasma EUV sources for 13.5 nm and beyond, which are included to the conversion efficiency and fast ion debris. In this presentation, we show the charge-separated suprathermal ions of Sn for 13.5 nm source and Gd for beyond EUV source. We also discuss the mirror matching and the laser source development for B-EUV source

Presenting Author

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

S37

Laser Development for SSMB EUV Light Source at THU

Lixin Yan, Xing Liu, Huan Wang, Xinyi Lu, Xiujie Deng, Alexander Chao, Wenhui Huang, Chuanxiang Tang

Laboratory of Accelerator, Tsinghua University, Beijing, China

High power extreme ultraviolet (EUV) radiation based on steady-state microbunching (SSMB) mechanism has great potential for the development of next generation advanced EUV lithography technology. To further demonstrate multi-turn SSMB physics at the Metrology Light Source (MLS) of the Physikalisch-Technische Bundesanstalt (PTB) in Berlin, we have developed a high repetition rate (6.25MHz) high power (~30kW peak power) pulsed laser with high phase stability (1/20λ) as the modulator, seeded by an iodine-frequency-stabilized CW laser. We're also being devoted to developing high power (~1MW) CW optical enhancement cavity (OEC) technologies which would support the construction of a real SSMB EVU light source. Recent progress on laser technology development for SSMB light source at Tsinghua University will be presented in this report.

Presenting Author

Lixin Yan graduated as a bachelor from Department of Engineering Physics, Tsinghua University in 2001, and got his PhD in Nuclear Science and Technology at THU in 2006. After two-year postdoc, he became an assistant professor at Department of Engineering Physics, Tsinghua University, and was promoted to be an associate professor in 2012. Now he is leading the effort to develop advanced laser technologies for accelerator applications including SSMB EUV light source, and also advanced linac-based and laser-based high power THz radiation and its applications.

S41

Dynamics of Mass Distribution of Liquid Tin Target

B. Liu,[1,2] R. A. Meijer,[1,2] J. Hernandez-Rueda,[1] D. Kurilovich,[3] H. Gelderblom,[4] and O. O. Versolato[1,2]

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2. *LaserLab, Vrije Universiteit Amsterdam*
3. *ASML, Veldhoven*
4. *Eindhoven University of Technology, Eindhoven*

We present a global picture of the mass distribution of liquid tin produced from ns-length Nd:YAG laser pulse impact on a microdroplet. Features including the sheet thickness, mass content on the sheet, fragment size and speed are experimentally studied by our shadowgraphy imaging system with its high spatial and temporal resolution. First, the evolution of the target thickness is estimated by using three different methods with various droplet sizes and laser pulse energies. The results indicate a several-ten-of-nanometer sheet formed after the impact, which further yields the amount of tin remaining on the sheet during the droplet expansion. The tin lost from the sheet ends up in a thick rim bounding the sheet, and in fragment droplets produced from ligament protrusions from this rim. By employing a double-framing camera, we are able to measure the speeds of individual fragment droplets. These measurements reveal a self-similar behavior enabling us to describe all fragment speeds by a single scaled, non-dimensional parameter – indicating full predictability of fragment speeds under any experimental condition. With further high-NA imaging optics, measurements of the size of the fragments becomes possible. The fragment sizes, together with the counted fragment number and the aforementioned speeds, provides a full picture of the mass and momentum shedding from the sheet. This full picture of the shedding dynamics would enable optimizing the amount of tin contained in the sheet while minimizing the volume contributing to fragment-droplet "debris" in industrial sources of EUV light.

Presenting Author

Bo Liu is currently a PhD student at the Advanced Research Center for Nanolithography (ARCNL) in Amsterdam, the Netherlands. His research background covers fluid dynamics, capillary flow, droplet deformation and droplet fragmentation, both experimentally and numerically. His present studies focus on interpreting how a tin micro-droplet responds to nanosecond laser pulses, mainly from the fluid-dynamic point of view. Prior to his current position, Bo Liu obtained his BSc in Mechanical Engineering at Harbin Institute of Technology, China (2015) and his MSc in Mechanical Engineering at Delft University of Technology, the Netherlands (2017). During his MSc studies, Bo did an internship at ASML where he completed his master thesis on 'Numerical simulation of oblique droplet impact on a liquid pool' under the supervision of Dr. Hanneke Gelderblom. Inspired by the topic of his MSc project, in 2017 Bo joined the EUV Plasma Processes group at ARCNL as a PhD student under the supervision of Dr. Oscar Versolato. So far, his research achievements have been recognized in form of publications in peer reviewed journals and contributions in international conferences.

S42

EUV Sources for High-volume Manufacturing (HVM): Performance and Availability in the Field, and Innovation Towards the Future (Invited)

Evan Davis, Igor Fomenkov, Michael Purvis, Alex Schafgans, Jayson Stewart, Peter Mayer, Klaus Hummler, Alex Ershov, Sam Crisafulli, Andrew LaForge, Yezheng Tao, Slava Rokitski, Chirag Rajyaguru, Georgiy Vaschenko, Payam Tayebati, Daniel Brown, David Brandt

ASML, 17075 Thornmint Ct, San Diego, CA 92127

ASML EUV scanners are installed at customer factories and are now being used in high-volume manufacturing (HVM) of leading semiconductor devices. This successful transition to HVM was partially enabled by fundamental improvements in the latest generation of EUV sources, which operate with high availability and generate 250 W of EUV power. Here, we provide an overview of the 13.5 nm tin laser-produced-plasma (LPP) extreme-ultraviolet (EUV) source. Progress in the development of key technologies for power scaling towards next-generation scanners will be described. This development is informed by fundamental studies of EUV generation and collection, including target formation, ion generation, the radiated spectrum, and spatiotemporal aspects of the EUV emission itself. Select experimental techniques and recent results will be reviewed.

Presenting Author

Evan works in Technology Development at ASML San Diego, where he has fielded a variety of spectrometers and imaging systems to study EUV generation and collection. Evan earned his PhD in physics at MIT in 2018 and his BS in physics and applied mathematics at the University of California, Riverside in 2010.

S43

Characterization of the Laser-Tin Droplet Interactions: Progress and Plans (Invited)

Ahmed Diallo

Princeton Plasma Physics Laboratory

Princeton Plasma Physics Laboratory has expanded its research portfolio and began embarking into microelectronics. Specifically, PPPL has embarked in EUV lithography with the goal of investigating the effects of various pulse shaping schemes on debris and providing a portable time-resolved Thomson scattering system to probe the laser-tin droplet interactions. As such, an EUV laboratory and a sub-ns Thomson scattering system are being designed and commissioned. In addition, we are also developing a particle-in-cell simulation of plasma ablation to study fast debris ion acceleration processes as well as the effects of pulse shaping on these debris. Simulations are conducted and initialized from profiles obtained from a radiation-hydrodynamics simulation, and we show initial results. Long term plans involve the addition of other advanced PIC codes such as WarpX (in collaboration with LBNL) WarpX is an advanced PIC code developed as part of the DOE Exascale Project and can run at scale on the latest DOE supercomputers, including GPU-based architectures. WarpX also has a number of important multi-physics modules (ionization, Coulomb collisions) and is routinely used to simulate the physics of laser-plasma interaction, including ion acceleration from laser-irradiated solid targets.

Presenting Author

Dr. Ahmed Diallo earned a Ph.D. in physics from the University of Iowa in 2005 after receiving a bachelor's degree from the University of Montana and a Diplome d'Etude Universitaire Generale from the University of Ouagadougou in Burkina-Faso. He served as a post-doctoral researcher at the École Polytechnique Fédérale de Lausanne in Switzerland from 2006 to 2008, then joined the Plasma Research Laboratory at the Australian National University as a research fellow in 2008 and the U.S. Department of Energy's Princeton Plasma Physics Laboratory in 2009. Dr. Diallo is a Distinguished Research Fellow at Princeton Plasma Physics Lab, Head of the Advanced Diagnostics Development Division and Deputy Director Innovation Network for Fusion Energy (INFUSE). He also served as the head of the pedestal and control topical science group for the National Spherical Torus Experiment-Upgrade (NSTX-U), the Laboratory's flagship fusion facility, and is the recipient of a 2013 Early Career Research Program grant from the DOE's Office of Science to conduct research into understanding and controlling the edge of fusion devices. His current research interests include pedestal physics, edge-localized modes, blob dynamics, thruster physics, laser-aided plasma diagnostics and basic plasma phenomena, and laser plasma-interactions. He is an author and co-author of more than 100 papers and has given many invited talks at APS Division of Plasma Physics meetings and other national and international scientific conferences.

S45

Effect of Laser Pulse Shapes on 13.5 nm Radiation Generation* (Invited)

Farhat Beg, Brian Lee, Kazuki Matsuo and Mathieu Bailly-Grandvaux
Center for Energy Research, University of California San Diego

Efficient generation of 13.5 nm light is extremely important for the Extreme ultraviolet (EUV) lithography. Simulations can help to optimize the laser-plasma interaction for an enhanced EUV light output. In this work, we benchmarked existing experimental data [1] using radiation hydrodynamics code FLASH and an atomic code SPECT3D. We show a reasonable agreement between experimental data and simulations. After benchmarking the code, we studied the impact of the laser temporal pulse shapes on energy conversion efficiency from the laser to EUV light. We found that progressively ramping up the pulse intensity at 1 μm wavelength results in a 4.0% improvement in conversion efficiency compared to a square pulse. We expect FLASH and SPECT3D to be the tools of choice for new researchers in EUV lithography.

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*We acknowledge support of ASML for this work.

Presenting Author

Farhat Beg is a Professor of Engineering Physics at the Department of Mechanical and Aerospace Engineering at the University of California, San Diego. He received his Ph.D. from Imperial College London. He joined University of California San Diego as a faculty in 2003. His expertise is in the field of inertial and magneto inertial fusion, laser plasma interaction, pulsed power-driven X- and Z-pinches, and neutron sources. He has published over 250 papers in refereed journals, including Nature, Nature Physics, Nature Photonics and Physical Review Letters, with total citations exceeding 9000 with and H-index of 49, according to the ISI Web of Knowledge. He is the fellow of the American Physical Society (APS), the Institute of Electrical and Electronics Engineers (IEEE) and the American Association for the Advancement of Science (AAAS). He has been a winner of the Department of Junior Faculty Award (2005) and IEEE Early Career Award (2008).

S48

Charge-separated Ion Spectra in Laser-produced Sn Plasma

Yuto Nakayama,[1] Takeru Niinuma,[1] Masaki Kume,[1] Hiromu Kawasaki,1 Atsushi Sunahara,[2] and Takeshi Higashiguchi[1]

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The 13.5-nm EUV lithography is operated in high-volume manufacturing of integrated circuits (ICs). Lithography at this wavelength is capable of reaching feature sizes below 5 nm. In order to modelling the laser-produced plasma EUV source, we should evaluate the charge-separated ion spectra in laser-produced Sn plasma as an initial condition under numerical simulation for debris mitigation. In presentation, we show the detail Sn ion spectra and some dependences.

Presenting Author

Yuto Nakayama is a graduate student in engineering at the Utsunomiya University. His research activities have focused on the atomic calculation to evaluate the UTA spectra from high-Z, highly charged ions in laser-produced plasmas for short-wavelength light sources.

S49

Development of an Experimental Setup to Measure Energy Transfer from Sn ions to H_2 Molecules at Collision Energies Below 10 keV

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Modern EUV sources based on a laser-produced plasma (LPP) use hydrogen as a buffer gas to slow down the fast Sn ions coming from the LPP. Further optimization of this technique by simulations requires accurate atomic data on the energy loss and charge exchange processes in collisions of Sn ions with H_2 molecules. At the ZERNIKELEIF facility in Groningen we can generate a beam of Sn ions of a pre-selected energy, charge state, and mass (isotope). We are upgrading our existing gas-target setup to measure energy transfer from Sn ions to H_2 molecules by time-of-flight spectroscopy. To obtain sufficiently high energy resolution it is important to have a localized gas target. I will present our characterization of the gas target profile flowing from a capillary. Furthermore, I will discuss our ion deceleration stage that enables us to measure Sn ion at energies below 10 keV.

Presenting Author

Klaas Bijlsma studied Applied Physics at the University of Groningen in The Netherlands and obtained his MSc degree in 2019. His master's research project involved developing an ion mobility spectrometer for biomolecular ions. He carried out an internship at the National Institute of Standards and Technology in the United States, where he worked on the measurement of nanoscale spin dynamics in thin film materials. Since November 2019 he is a PhD student at the University of Groningen, in collaboration with the Advanced Research Center for Nanolithography (ARCNL). His research topic is the interaction of energetic tin ions with hydrogen gas.

S50

Development Progress of the Key Component Technology for the High Power LPP-EUV Light Source

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For high volume manufacturing EUV (λ=13.5nm) lithography, Gigaphoton have been developing a carbon dioxide laser produced tin (Sn) plasma (CO_2-Sn-LPP) EUV light source system, named Pilot#1. To several factors shorten the operation availability of Pilot#1, such as degradation of the multilayer coating[1] and Sn deposition of the collector mirror. We have already demonstrated a collector mirror reflectivity degradation rate of -0.5%/billion pulses at an average power of 125W during about 30 billion pulses operation, with our original Sn mitigation system using a super-conductive magnet and a controlled chamber hydrogen gas flow[2]. Furthermore, we have optimized the laser irradiation condition for the YAG pre-pulse laser and CO_2 driver laser to suppress the generation of high-energy Sn ions without loss of the high EUV Conversion Efficiency (CE) of ~6% and achieved 365W in short-term operation and 270W in mid-term with Pilot#1.

To improve the availability of Pilot#1, long term performance of new droplet generator with in-situ Sn fuel feed system is under testing. Stable droplets were generated continuously for over 2,000 hours. We are continuing testing with the target lifetime of 9,000 hours of continuous operation.

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Presenting Author

Yoshiyuki Honda joined the Advanced Light Source Research Division of Gigaphoton inc. in 2016 and started research and development of carbon dioxide laser produced tin plasma (CO_2-Sn-LPP) EUV light source. His main research is in optimization of the control parameters for tin plasma generation for EUV light source and elucidation of the degradation mechanism of the collector mirror protective films.

He is a member of The Japan Society of Applied Physics and authored one paper on the degradation of protective films at APEX in October 2020.

S76

Tailoring the Expansion-to-Propulsion Ratio of Laser-induced Tin Targets for Extreme-ultraviolet Nanolithography

Javier Hernandez-Rueda,[1] Bo Liu,[1, 2] Diko J. Hemminga,[1, 2] Yahia Mostafa,[1, 2] Randy A. Meijer,[1, 2] John Sheil,[1] and Oscar O. Versolato[1, 2]

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The precise control over the shape, size, and dynamic features of laser-generated tin targets highly conditions the efficiency and durability of extreme-ultraviolet sources for nanolithography. The laser-tin interaction generates a plasma, whose rapid expansion imprints a pressure impulse at the surface of liquid tin microdroplets. Its spatial distribution strongly affects the momentum balance between driving radial deformation and axial propulsion of tin droplets. In this work, we investigate the influence of the droplet and laser beam diameters on the pressure impulse that ultimately leads to a large variety of deformation/propulsion ratios. Using stroboscopic shadowgraphy, we record the evolution of the liquid tin morphology and determine the propulsion speed U and expansion rate $\dot{R}$. We find excellent agreement between experimental U and $\dot{R}$ values and those obtained by radiation-hydrodynamic simulations (RALEF-2D). From the simulations, we extract the pressure impulse at the droplet surface and the relationship between its width and the $\dot{R}/U$ ratio. We quantitatively show how the width of the pressure impulse determines the balance between driving radial deformation and axial propulsion. Finally, we compare our findings on the pressure impulse with computational fluid dynamics simulations to gain further insight, and to link the initial plasma-driven dynamics (nanosecond-scale) to the subsequent fluid dynamics (microsecond-scale).

Presenting Author

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

S51

New Approaches for Coherent Extreme-ultraviolet Generation and Manipulation from Solids (Invited)

Peter Kraus

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The generation of extreme ultraviolet and soft-X-ray pulses by high-harmonic generation (HHG) is the workhorse of attosecond science [1] and enables the observation of ultrafast electronic and nuclear dynamics in molecules and solids [2]. Importantly, the introduction of extreme-ultraviolet lithography into the high-volume manufacturing of integrated circuits now created the first potential industrial applications of high-harmonic sources [3,4].

The recently discovered solid-state high-harmonic sources provide new opportunities for extreme-ultraviolet generation and manipulation at will through nano-engineering of the emitting sample.

In this talk, I will introduce new concepts developed in our group to use high-harmonic emission from solids to perform direct metrology on nanoscales samples, manipulate the emitted XUV fields at will, and image aperiodic structures well below the diffraction-limit of the fundamental radiation.

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Presenting Author

Peter Kraus has been tenure-track group leader at ARCNL since May 2018, and assistant professor of physics at the Vrije Universiteit Amsterdam. Peter Kraus is leading a program to develop extreme ultraviolet (EUV) sources from high-harmonic generation and apply them for ultrafast spectroscopy and nanoscale metrology experiments with relevance to nanolithography.

Prior to joining ARCNL/VU, Peter Kraus worked at the University of California, Berkeley (USA) on the development of new experimental techniques for investigating attosecond phenomena in solid-state materials.

Peter Kraus obtained his PhD at ETH Zurich (Switzerland) in 2015. Here, he developed and advanced the techniques of high harmonic-spectroscopy for investigations of electronic and nuclear structure and dynamics of molecular systems.

S52

Compact EUV Spectrometry Tool for Thin Film and Nanograting Characterization (Invited)

Sascha Brose[1,2], Sophia Schröder[1,2], Lukas Bahrenberg[1,2], Henning Heiming[1,2], Serhiy Danylyuk[3], Jochen Stollenwerk[1,2,3], and Carlo Holly[1,2]

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The introduction of EUV lithography for the high-volume manufacturing of integrated circuits led to a demand for accurate metrology techniques in various fields connected to the manufacturing process. Using a broadband EUV emission spectrum allows for high-throughput spectroscopic metrology approaches, suited for thin film and structured film characterization. This broadband radiation is provided in a wavelength range from 10 nm to 15 nm by discharge-produced plasma (DPP) EUV radiation sources. Relevant materials like mask absorbers, pellicles or photoresists can be characterized by measuring their reflectance (or transmittance) at multiple grazing incidence angles. Through analysis of these multi-angular spectroscopic measurements, the layer thicknesses, the material's refractive index and even the geometric parameters of a periodically structured surface are determined.

The realized stand-alone EUV spectrometry tool utilizes a compact DPP EUV source for illumination of the investigated sample. The xenon emission spectrum is measured before and after sample interaction by two sequential spectrographs, each consisting of a diffraction grating and a two-dimensional charge-coupled device camera. By comparing both spectra, the reflectance is calculated within the wavelength range and used for a model-based parameter reconstruction. The presented studies set a basis for the development of an industrial EUV spectrometry tool that can be used for (inline) process control in advanced lithographic processes for future nodes.

Presenting Author

Dr. Sascha Brose graduated in mechanical engineering in 2008 and received the Ph.D. degree in mechanical engineering in 2019 from RWTH Aachen University. Since 2019, he is group manager of the research group “EUV technology” at the Chair for Technology of Optical Systems (TOS) at the RWTH Aachen University. Since 2009 he is working in the field of applications for the extreme ultraviolet (EUV) at the RWTH Aachen University concentrating on the conceptual design and construction of EUV tools for high-precision metrology and nanoscale patterning. His research fields include EUV proximity and interference lithography, EUV reflectometry/scatterometry and material modification by focused EUV radiation. Additionally, he is expert in micro- and nanofabrication processes of optical components like spectral filters and diffraction gratings especially designed for EUV wavelengths. He has authored and co-authored more than 30 scientific publications mainly in the field of EUV lithography and metrology.

S53

Herriott Cell Based Nonlinear Compression (Invited)

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Ultrafast lasers allow for a variety of applications in science and industry due to their extremely high peak powers. Many of these applications require not only high peak powers but also high repetition rates and therefore high average powers. Ti:Sa-based systems deliver pulse durations well < 50fs but are limited in average power to a few watts [1,2], whereas ultrafast Yb-based systems can achieve average powers of nearly 2kW [3] and a few kW in perspective, but with longer pulse durations typically ~1ps. Nonlinear pulse compression could combine Yb-based systems with simultaneously high average power, high pulse energies in the mJ-range and short pulse durations < 50fs. Nonlinear pulse compression is based on nonlinear spectral broadening by self-phase modulation (SPM) followed by spectral phase compensation realized for example in a chirped mirror compressor.

Well established schemes for nonlinear compression are often using waveguides, such as fibers or capillaries. However, these waveguides are subject to several limitations, making them inapplicable for high pulse energies or high optical transmission efficiencies [4,5].

By using a ~2.5m long Argon filled Herriott cell as nonlinear medium, we demonstrate the compression of 630fs long pulses from a thin-disk regenerative amplifier to 36fs with 10mJ of pulse energy at 3kHz repetition rate (Fig. 1a). The beam quality measured after the nonlinear pulse compression is excellent with M^2 <1.2 and enables very good focusability (Fig. 1b). The nonlinear compression is almost free of losses and achieves an optical efficiency of >95%. In addition, we show our current high-energy development which makes it possible to compress pulses with an energy of 200mJ to less than 50fs with an average power of 1kW. Such laser sources could give rise to a manifold of exciting applications such as inverse Compton scattering [6], high harmonic [7] and X-ray generation [8], laser wakefield accelerator-based light sources [9] and laser-driven neutron sources [10].

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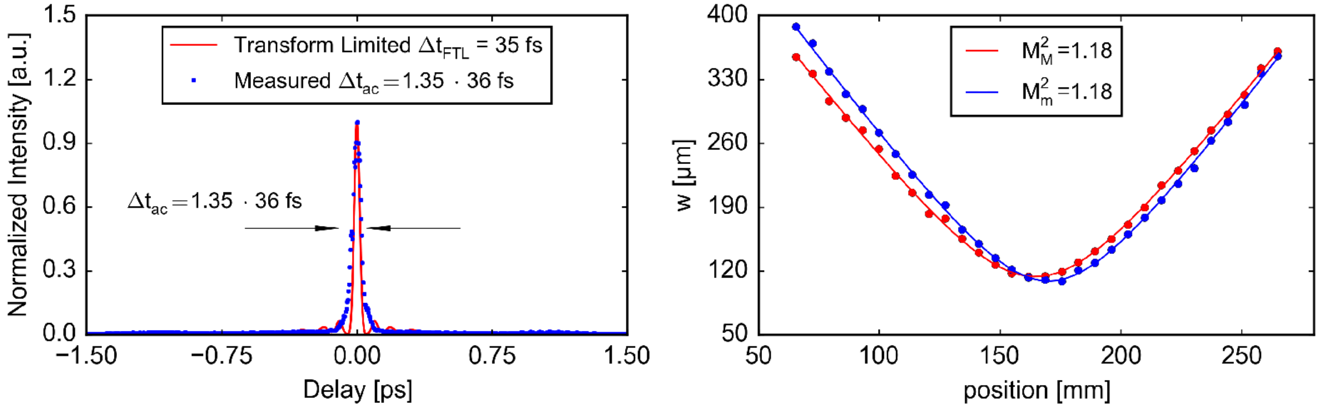

Fig. 1. a) Autocorrelation and b) Beam quality measurement of the compressed output pulses.

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Presenting Author

Yanik Pfaff studied mechanical engineering at the Technical University in Munich and received his M.Sc. in 2020. After his degree he started his PhD at TRUMPF Scientific Lasers GmbH + Co. KG. and in cooperation with the research group of Prof. Clara Saraceno at the Ruhr University Bochum. His work concentrates on increasing laser peak powers by using nonlinear compression schemes.

S54

kW-class Picosecond Thin-disk Lasers with Diffraction-limited Beams at HiLASE Facility (Invited)

M. Smrž, J. Mužík, M. Chyla, J. Huynh, P. Sikocinski, J. Cvrček, O. Novák, H. Turčičová, M. Cimrman, D. Štěpánková, M. Duda, and T. Mocek

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Advent of thin-disk lasers in 90s opened a path towards multi-kW sources of nanosecond and picosecond laser pulses. Nowadays, thanks to combination of picosecond pulses, high beam quality, and high pulse energy, Yb-doped lasers based on this technology became a powerful tool for hi-tech industrial and scientific applications, including applications in generation of EUV photons. They are frequently employed, for example, like pre-pulse systems in laser-produced plasma-based photon sources for EUV lithography. High-energy systems also serve as sources of laser-produced-plasma emitting EUV and x-ray photons. HiLASE centre made a progress in improvement of thin disk laser platform called Perla, which is available in versions based on Yb and Ho doped materials. With additional nonlinear frequency conversion can be currently covered spectral range from UV to mid-infrared (up to wavelength of >4-um). Our laser platform reaches sub-kW average power sufficient for majority applications, however, the unique property of the Perla laser is beam quality parameter M^2 as low as 1.1, i.e. almost diffraction limited beam. This is extremely important for applications integrating diffractive optical elements or applications aiming at the highest intensity in beam focal position. This enabled us to reach several unique scientific results. With the diffractive optical elements, we were able to generate > 40,000 beams for simultaneous processing of 40,000 positions. We also managed to generate alpha particles after irradiation of targets by 20-mJ picosecond pulses. Fully automated industrial version of the Perla platform is available from the HiLASE. The industrial systems can be tailored upon customer’s needs. Alternatively, beam time of the lasers can be provided at HiLASE labs in Czechia. Our next focus is also directed towards Ho-based disk lasers emitting close to wavelength of 2-um, next beam improvements at higher pulse energy, an spectral broadening to femtosecond regime.

Presenting Author

Martin Smrz received his PhD degree in applied physics in 2012 from the Czech Technical University in Prague, Czechia. Since 2012, he has been with the HiLASE centre, Institute of Physics AS CR, interrupted by fellowships at Massachusetts Institute of Technology (USA), or Centre for free electron laser of DESY in Germany. Since 2018 he got a group leader of ultrashort pulse thin disk laser development group, and since 2020 he is a leader of Advanced laser development dept. at the HiLASE centre. His current research focuses on high power lasers for industrial and scientific applications.

S61

High-brightness EUV LPP Source based on Fast-rotating Target (Invited)

M. Krivokorytov[1,2], V. Gubarev[1,2], V. Ivanov[1,2], V. Krivtsun[1,2], A. Vinokhodov[2], V. Medvedev[1,2], E. Gorsky[4], A. Kiselev[4], D. Glushkov[3], S. Ellwi[3], A. Lash[1], K. Koshelev[1,2]

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Laser plasma is the most attractive approach for constructing power-scalable high-brightness sources of extreme ultraviolet radiation for industrial applications in lithography and related technological processes. Sources using tin-based plasma provide the highest conversion factor of the input energy of laser pulses into the energy of useful radiation pulses in the wavelength range near 13.5 nm. The main technological challenge arising from the use of tin-based plasma is to control and suppress the fluxes of corpuscular debris arising in the process of laser ablation of the target material. In this paper, we describe in detail the methods for suppressing all possible fractions of debris (plasma, vapor, and microdroplets) in the TEUS source we are developing, which uses a Nd:YVO4 laser (1064 nm, 1.5 ns, 4 mJ, 100 kHz) and a fast-rotating (200 Hz) target.

References

[1] ISTEQ - TEUS EUV Light Source

Presenting Author

Slava Medvedev received his Ph.D. degree in 2015 from University of Twente, The Netherlands. His thesis was devoted to the development of extreme ultraviolet mirrors with improved spectral characteristics. Then he went to work in the Department of Atomic Spectroscopy of the Institute of Spectroscopy of the Russian Academy of Sciences (ISAN). At ISAN he works in a group that is developing various plasma radiation sources with private companies EUV Labs and TRDC.

S62

Modeling a Discharge Produced Plasma (DPP) EUV Source (Invited)

David Reisman

Energetiq Technology, Inc., Wilmington, MA 01887, USA

The EQ-10 Electrodeless Z-pinch™ source uses Xenon plasma to produce 13.5 nm (±1% BW) radiation. The source is used for metrology, mask inspection, and resist development. In this talk we will present modeling of the EQ-10 Z-pinch using Trac-II, a radiation-MHD code. In 1D calculations, we explore the energy balance of the pinch which is strongly influenced by ohmic heating and radiation. Such calculations give us important parameters such as temperature and density which in turn determine EUV output and conversion efficiency (CE). We also discuss the importance of non-LTE physics in radiation physics and the equation of state. In 2D calculations, we look at the impact of the magnetic Rayleigh-Taylor (MRT) instability and discuss how we may use stabilization strategies to increase the CE. Lastly, we discuss the modeling of alternative gases to produce 6.x nm (Blue-X) sources.

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).

S63

Update on LPP Source Development at ETH Zurich (Invited)

Reza Abhari

ETH Zurich

ETH Zurich has been developing a droplet-based laser produced plasma (LPP) light over the last 14 years, initially focused on the needs of actinic mask inspection while later expanding to other applications. Here, latest technical improvements in the brightness and operational capability of the LPP light source will be presented. Having previously demonstrated EUV brightness measurements of over 350 W/mm2 Sr, the extendible light source would fulfill all the technical requirements of mask and wafer inspection systems for the present and many future nodes, lowering technology risks for future upgrades. The small footprint of the source as well as state of the art platform damping technology ensures that the light source can be seamlessly integrated into the inspection tool.

The main focus of the research team has been to increase operational stability and output brightness of a cost-efficient Nd:YAG driven laser-produced plasma source. Advances have been made in the fields of stable regenerative microdroplet target generation, optimization of laser-target interaction and debris mitigation. Last year, the laser parameters were further fine-tuned resulting in an optimized laser-target interaction, as reflected in the increased source conversion efficiency ($CE = E_{EUV}/E\_laser$) from 1.09% (mid-2020) to 1.8% (spring 2021) with a factor of 1.7 increase in the source brightness. Another important improvement in the increased EUV source output performance is attributed to the optimized debris mitigation parameters, which have been further optimized to lower the total optical opacity in the EUV inband range, having a strong dependence on the source operational frequency. The optimized debris mitigation increases the measured EUV source emission at a distance of 300 mm from the source by up to 15%. In addition, the new V8 droplet generator has shown great versality, allowing a highly stable and controllable increase in the spacing of over 15 droplet diameters, completely attenuating the effect of the plasma pressure wave on the subsequent droplets. These achievements were reached without compromising the lateral laser-target alignment. EUV energy pulse to pulse stability was improved by reducing the inter-droplet timing jitter, minimizing the laser pulse energy fluctuation interacting with the regenerative microdroplet target on a pulse-to-pulse basis.

Future plans for light source research and development will also be presented.

S64

Irradiation Systems for Accelerated Testing of EUVL Components (Invited)

Jochen Vieker and Klaus Bergmann

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Steinbachstr. 15, 52074 Aachen, Germany

Fraunhofer ILT has been developing EUV sources for more than 2 decades. In collaboration with Philips and Ushio, ILT has contributed to the development of discharge-based sources, which have been operated in the first EUV lithography scanners for chip production.
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 design of the system allows multiplexing to reach 10 kHz and a higher power on sample. An updated design and new results based on optical and gas-flow simulations will be presented.

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.

S65

High-brightness LDP Source: Variation of EUV-emitting Plasma (Invited)

Yusuke Teramoto[1], Bárbara Santos[1], Guido Mertens[1], Margarete Kops[1], Ralf Kops[1], Wilko van Nunspeet[1], Marcel Schneider[1], Klaus Bergmann[2], Yoshihiko Sato[3]

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[3]Ushio Inc., 1-6-5 Marunouchi, Chiyoda-ku, Tokyo 100-8150, Japan

The Laser-assisted discharge-produced (LDP) plasma EUV sources are used at the EUV irradiation facility [1] and in the actinic mask inspection tool [2]. The sources are used at various frequencies, and capable of running at 10 kHz generating approximately 250 W/mm^2/sr of EUV brightness. This paper focuses on variation of an EUV-emitting LDP plasma. The laser-produced plasma, which is used to trigger the pulsed discharge, was diagnosed using a time-integrated spectrometer and a high-speed gated camera. The discharge plasma, which was driven by a few-kA, 150-ns pulsed current, was observed with the gated camera to see the plasma explodes and implodes during the discharge process. An emission spectrum in EUV range was observed using a grazing-incidence spectrometer. An energy distribution of ions emitted from the Sn plasma was measured with a Faraday cup using the Time-Of-Flight method. The experimental results showing the event of each stage of EUV generation from plasma generation to EUV and fast-ion emission will be presented. In addition, some latest updates from the sources in the field will be presented.

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Presenting Author

He received Ph.D. degree in 2002 from Kumamoto University, Japan. He joined Ushio Inc., Japan in April 2002 and started research and development of Xe- and Sn-fueled discharge EUV sources. In 2008, he moved to Aachen, Germany to participate the co-development program between Ushio, XTREME, Philips and Fraunhofer ILT. He engaged in the EUV source development, especially in power scaling. Now he is working for Ushio Germany GmbH, an Ushio group company. He is currently the manager of R&D Section 1 of EUV Business Unit managed by Ushio Inc. and working on EUV and X-Ray sources research and development.

S73

Compact Rotating Sn Disc Target LPP Source

Yusuke Teramoto[1], Bárbara Santos[1], Guido Mertens[1], Margarete Kops[1], Ralf Kops[1], Wilko van Nunspeet[1], Marcel Schneider[1], Klaus Bergmann[2], Yoshihiko Sato[3]

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The laser-produced plasma (LPP) EUV source is developed at Ushio Germany in cooperation with Fraunhofer ILT. The source utilizes a rotating disc target coated with liquid tin and a solid-state nanosecond laser. Its compact design has a potential to provide EUV photon to various applications. The source was designed to run at up to 50 kHz and the current tests are underway at 20 kHz. The source has a debris filter and a collector so that the focused EUV light is available at the intermediate focus point. In this poster, the latest update on the development work will be presented.

Presenting Author

He received Ph.D. degree in 2002 from Kumamoto University, Japan. He joined Ushio Inc., Japan in April 2002 and started research and development of Xe- and Sn-fueled discharge EUV sources. In 2008, he moved to Aachen, Germany to participate the co-development program between Ushio, XTREME, Philips and Fraunhofer ILT. He engaged in the EUV source development, especially in power scaling. Now he is working for Ushio Germany GmbH, an Ushio group company. He is currently the manager of R&D Section 1 of EUV Business Unit managed by Ushio Inc. and working on EUV and X-Ray sources research and development.

S75

Fabrication of EUV Light Source with Cold-Cathode Electron Beam (C-beam)

Sung Tae Yoo, and Kyu Chang Park*

Department of Information Display, Kyung Hee University, Dongdaemun-gu, Seoul, 02447, Korea

Electron beam irradiation on various materials used for lighting, display, microscope, and medical devices application. Cold cathode electron beam with carbon nanotube (CNT) electron sources developed for novel vacuum nano-electronic devices. We developed novel cold cathode-based electron beam using CNT emitters, called as C-beam and applied it to an EUV light generation source. UV generation of various wavelengths was studied using C-beam as an energy source. Excitation of various anode targets such as AlGaN MQW, Sapphire, SrB_4O_7:Eu and Zn_2SiO_4 anodes have already been reported [1],[2]. Large-area UV light sources from UVA to UVC were obtained. Based on these studies, we developed a novel EUV light source with C-beam irradiation technique.

Unlike laser-produced plasma (LPP) technology, C-beam technology directly irradiates electrons to the tin anode, and EUV generated in cold plasma was obtained. EUV generation by direct irradiation of electrons on tin anode was confirmed using a polymethyl methacrylate (PMMA) photoresist lithography and a EUV photodiode equipped with a 150 nm thick Zr filter [3]. EUV intensity depends on C-beam parameters with anode voltage, current, and dc pulses. Further details will be presented.

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Presenting Author

Sung Tae Yoo received the B.S. degree in mechanical engineering from Chungbuk National University, Republic of Korea, in 2013 and the M.S. degree in Department of Information Display from Kyung Hee University, Republic of Korea, in 2017. He is currently pursuing the Ph.D. degree in Department of Information Display from Kyung Hee University, Republic of Korea. His technical interests are in the EUV & UV light source, field emission, carbon nanotube.

S66

Broadband Metrology of EUV Light Sources (Invited)

Muharrem Bayraktar

Industrial Focus Group XUV Optics,
University of Twente, Enschede, The Netherlands

In developing the next generation of high power EUV light sources, characterization of their energy, power, and spectral characteristics is a vital step. For the EUV lithography tools, metrology of the in-band energy around the 13.5 nm (±1%) is important for the dose control. Besides the in-band emission, EUV lithography light sources also emit in a broad wavelength range from soft x-rays to visible wavelengths. A broadband metrology is thus required for monitoring and optimization of these light sources for enhanced in-band and reduced out-of-band emission.

Here, a selection of metrology tools developed in University of Twente is reviewed. The first part presents absolutely calibrated in-band energy metrology tools. First tool is based on a photodiode that is combined with a multilayer mirror acting as the wavelength limiting element. The second in-band tool is a compact alternative that is composed of a photodiode coated with a narrowband transmission coating based on anomalous transmission principle. The second part presents a transmission grating spectrometer based on a set of free-standing gratings for broadband spectroscopy. Using this transmission grating spectrometer, several light sources including high harmonic generation, discharge produced plasma and laser produced plasma, are measured. The spectral characteristics of these EUV light sources are presented in a broad wavelength range, for some, spanning from soft x-rays to visible wavelengths.

Presenting Author

Muharrem Bayraktar earned his BSc degree from Bilkent University in 2007, MSc degree from Sabanci University in 2010 and PhD degree from University of Twente in 2015. He is working as an assistant professor in the Industrial Focus Group XUV Optics in University of Twente since 2019. His research explores broadband spectroscopy techniques and novel adaptive optical components based on piezoelectric thin films for extreme ultraviolet wavelengths.

S67

Hybrid Metrology Assisted Determination of Optical Constants in the EUV Spectral Range (Invited)

Qais Saadeh,[1] Philipp Naujok,[2] Vicky Philipsen,[3] Philipp Hönicke,[1] Christian Laubis,[1] Christian Buchholz,[1] Anna Andrle,[1] Christian Stadelhoff,[1] Heiko Mentzel,[1] Anja Schönstedt,[1] Victor Soltwisch,[1] and Frank Scholze[1]

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So-called mask 3D effects, sacrificing the image contrast on resist, need to be mitigated for the further development of Extreme Ultraviolet Lithography (EUVL). Using alternative absorber alloys is a potential solution [1]. A meaningful material screening requires reliable optical constants.

Optical constants can be determined by either angle-dependent reflectometry at bulk samples or transmission measurements of thin foils. The latter is challenged experimentally by the preparation of the thin free-standing foils particularly for highly absorbing materials as of interest here. Additionally, to obtain delta from beta using Kramers-Kronig analysis, it requires a reliable compilation of optical data for the whole electromagnetic spectrum, which is often missing.

Reflectometry, on the other hand, requires an inverse-problem solving strategy to derive delta and beta from the measured reflectance and, experimentally, it may suffer from surface roughness and contamination. The parametrized geometrical model of the sample under test, built on prior knowledge, is therefore pivotal to correctly account for those effects.

Here, we present an approach to derive the model of the sample based upon analyzing angle-dependent X-ray Reflectivity (XRR) using time-frequency analysis [2], enabling an assertive substitute for the trial-and-error scheme. Additionally, we use a Markov-Chain Monte-Carlo (MCMC) sampling technique coupled with Bayesian inferences, that detects potential multi-modalities in the searched parameter space and provides uncertainty estimates of the determined parameter values.

We present optical data for candidate alternative EUV absorber materials as determined using this approach [3].

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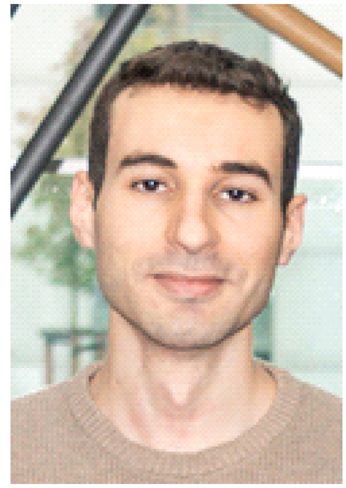
Presenting Author



After majoring in physics in the University of Jordan (2013), Qais continued for a European joint M.Sc. degree program in Functionalized Advanced Materials and Engineering, with studies taking place in the University of Augsburg (2016) and Grenoble Institute of Technology (2017). After that, Qais worked in the Federal Institute for Materials Research and Testing in Germany on developing In-Situ characterization techniques of magnetic nanoparticles. In early 2019 Qais joined the PTB as a doctoral researcher, focusing on the determination of optical constants for technological materials relevant for the EUVL optics.

S68

EBL2 Upgrades and Upcoming Extensions (Invited)

Norbert Koster

TNO, Stieltjesweg 1, 2628 CK Delft, The Netherlands

Recently EBL2, TNO's EUV exposure facility for optics lifetime testing has been upgraded with a IR hot spot camera to measure EUV induced temperature profiles in optics and pellicles with high lateral resolution and without contacting the sample. We will report on the first results obtained with this camera on samples exposed to EUV. Besides the upgrade with the IR camera another upgrade is foreseen with an EUV reflectometer. This reflectometer will be mounted on the exposure chamber of EBL2 and be capable of doing relative reflectivity measurements on the samples and pre and post comparisons during the experiments. This will give valuable additional information about the experiment and can shorten EUV exposure cycles. Because the reflectometer measures in situ the samples are not exposed to atmospheric conditions before measurement. This prevents surface oxidation as normally will happen when samples are exposed to atmosphere before shipping to reflectometry tools. By using a special designed reference mirror it is possible to perform absolute reflectivity measurements. As EBL2 is fully occupied with customer exposures the installation of the reflectometer has been delayed to 2022. We will report on the basic design of the reflectometer and expected performance.

Presenting Author

Norbert Koster is Principal Scientist at TNO in the group for Nano-instrumentation, he has worked in vacuum technology and EUV lithography since 1992. After graduation he worked at the former FOM Institute for Plasma Physics Rijnhuizen. There he was involved in the fabrication and optimization of Multilayer Mirrors for EUVL applications and space astronomy as well as the improvement of the deposition tools. In 1999 he started at TNO as vacuum engineer. Together with ASML and partners he stood at the birthplace of the EUV Alfa demo tools and their successors. During his career he developed interest in vacuum engineering, systems engineering and contamination control. As Principal Scientist he is involved in projects for EUV Lithography, plasma technology, contamination control, nuclear fusion (ITER).He was deeply involved in the realization of a new EUV exposure facility (EBL2) for EUV optics lifetime research at TNO in Delft.

S74

Highly Efficient Ultra-Low Blaze Angle Multilayer Grating as a Spectral Purity Filter for EUV Lithography

Sooyeon Park, Dmitriy L. Voronov, Eric M. Gullikson, Fahard Salmassi and, Howard A. Padmore

Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA

We have developed a process for the manufacture of highly efficient blazed multilayer gratings which can be used as a spectral purity filter for EUV lithography. Diffraction from the grating provides angular separation of the 13.5 nm wavelength EUV radiation from infrared and out-of-band deep ultraviolet radiation as suggested by K. C. Jonson [1]. To avoid excessive dispersion of the EUV radiation which would cause a reduction in apparent brightness, the grating should have a period of 5 - 10 μm. At the same time, to maximize efficiency, the grating grooves should have an ultra-low blaze angle below 0.1° to provide matching of the groove depth to the multilayer d-spacing. Fabrication of such low aspect ratio structures is not possible with existing grating fabrication techniques. We developed a process which starts with a relatively easy to make grating with a few degrees blaze angle and reduces this down to an ultra-small angle.

The blaze angle reduction process is based on planarization of a coarse blazed grating followed by a chemically selective plasma etch with an optimized etch rate ratio for Si and the material of the planarization layer. This provides a way to adjust the blaze angle to any lower value with high accuracy. Here we demonstrate the reduction of the blaze angle to an extremely low value of 0.04°±0.004°. For a 100 lines/mm grating with a Mo/Si multilayer coating, the grating exhibits diffraction efficiency of 58% in the 1st diffraction order at a wavelength of 13.3 nm [2].

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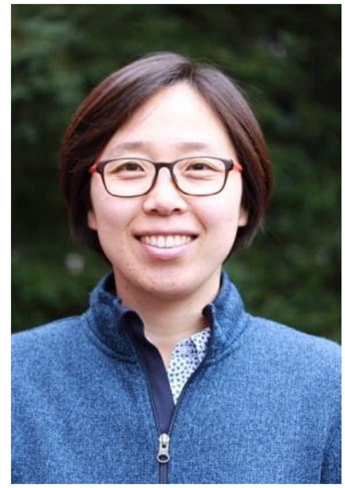
Presenting Author



Sooyeon Park is working to fabricate the low blaze angle gratings for ALS and ALS-U as a Project Scientist in Lawrence Berkeley Lab. She has got Ph.D. for new nanofabrication process development based on nanoimprint in University of Science and Technology in South Korea.

S71

Update from ARCNL's EUV Source Department on Spectroscopy, Generation of Energetic Tin ions and their Interactions with H2 and Generating Plasma with Laser Light of 2 µm Wavelength. (Invited)

Ronnie Hoekstra[1,2], Luc Assink[2], Muharram Bayraktar[3], Lars Behnke[1], Klaas Bijlsma[1,2], Zoi Bouza[1], James Byers[3], Diko Hemminga[1,4], Adam Lasisse[1], Zeudi Mazzotta[1], Yahia Mostafa[1], Lucas Poirier[1], Subam Rai[1,2], Mart Salverda[2], Joris Scheers[1,4], Ruben Schupp[1,4], John Sheil[1], Pieter Wolff[2], Wim Ubachs[1,4], Oscar Versolato[1,4]

1 - Advanced Research Center for Nanolithography (ARCNL), Amsterdam, the Netherlands
2 - Zernike Institute for Advanced Materials, University of Groningen, Groningen, the Netherlands
3 - Industrial Focus Group XUV Optics, MESA+, University of Twente, Enschede, the Netherlands
4 - Department of Physics and Astronomy and LaserLaB, Vrije Universiteit, Amsterdam, the Netherlands

In this talk ARCNL's progress on the following topics related to EUV light generation by a laser-produced tin plasma is reviewed:

- The measurement of a calibrated wide range (5 – 265 nm) emission spectrum of a Sn LPP plasma.
- Cross calibration of ESA-ToF, RFA, and Faraday Cup measurements of energy spectra of ions coming from the LPP droplet source.
- Predictions of such ion energy distributions by a single-fluid hydrodynamic model.
- Charge exchange interactions of Sn^{3+} ions traversing H_2 gas, energy and isotope effects.
- The generation of LPP plasma droplet source driven by a 2- µm wavelength laser and comparison of its specs to ones of a 1-µm driven LPP.

S72

Non-LTE Modeling of Sn Plasmas (Invited)

J. Colgan[1], A. J. Neukirch[1], J. Sheil[2] and O. O. Versolato[2]

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[2]*Advanced Research Center for Nanolithography, Science Park 106, 1098 XG Amsterdam, The Netherlands*

We continue our modeling of the radiative properties of tin plasmas at conditions relevant to EUV lithography. Previous work by us has demonstrated the importance of multiply excited states to the EUV emission spectrum of Sn plasma [1]. Recent work has also explored non-LTE effects in Sn plasmas at densities relevant to CO2 laser-produced plasmas [2]. In this presentation, we continue our efforts in this area, and examine non-LTE modeling that includes treatment of realistic radiation intensity distributions. That is, we consider the effect of the intensity distribution from a Sn laser-produced plasma on the non LTE kinetics of the plasma. Intensity distributions from both YAG and CO2 laser-produced plasmas are considered. Our calculations are made using the Los Alamos ATOMIC code [3,4]. ATOMIC has been used to calculate opacity tables under the assumption of LTE but can also be used in a non-LTE mode. The plasma simulations utilize atomic structure and transition data from the Los Alamos suite of atomic physics codes [5,6].

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This project has received funding from European Research Council (ERC) Starting Grant number 802648 and is part of the VIDI research programme with project number 15697, which is financed by the Netherlands Organization for Scientific Research (NWO). Part of this work has been carried out at the Ad vanced Research Center for Nanolithography (ARCNL). Work at Los Alamos supported by the ASC PEM Atomic Physics program. Los Alamos National Laboratory is operated by Triad National Security, LLC for the National Nu clear Security Administration of the U.S. Department of Energy (Contract No. 89233218NCA000001).

S81

INTRODUCTION TO ARCNL

Joost Frenken

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

The Advanced Research Center for Nanolithography (ARCNL) in Amsterdam (www.arcnl.nl) is a unique, long-term public-private partnership between the Dutch Research Council, NWO, the two universities in Amsterdam, UvA and VU, and the semiconductor equipment manufacturer ASML. The mission of ARCNL is to conduct basic research in physics and chemistry with relevance to present and future key technologies in nanolithography, primarily for the semiconductor industry. In this introduction, the brief history of ARCNL will be sketched and an overview will be provided of ARCNL's research program.

Presenting Author

Joost Frenken is the Founding Director of ARCNL and a Professor of Physics at both universities in Amsterdam (UvA and VU). Frenken's own scientific expertise is in the atomic-scale structure, diffusion, chemical reactions, phase transitions and friction phenomena at surfaces and interfaces, investigated with advanced instruments, developed under his supervision. His achievements have been recognized in several research awards and a membership of the KNAW, The Royal Netherlands Academy of Arts and Sciences. Frenken has (co)-initiated two companies, *Leiden Probe Microscopy BV* and *Applied Nanolayers BV*.

S82

Materials Research at ARCNL: The Many Interfaces of EUV Lithography

Roland Bliem

ARCNL, Science Park 106, 1098 XG Amsterdam, The Netherlands

High-quality, long-term performance of components throughout EUV scanners requires the use of materials that are optimized for the challenging conditions in extreme ultraviolet lithography (EUVL). Targeted improvements of state-of-the-art materials, however, demand fundamental insights into the interaction processes that are at the root of degradation and wear processes. In this presentation, we will introduce the ARCNL Materials Department and our approach to understanding the physical and chemical interactions at interfaces in EUVL, ranging from the degradation of EUV optics in harsh environments to friction and wear at the wafer table. The *Nanolayers* group focuses on the stability of thin films of scanner materials and their evolution under conditions relevant to EUVL. The surface chemistry of such materials is investigated using in situ photoelectron spectroscopy in reactive environments in the *Materials and Surface Science for EUV Lithography* group. Moreover, these two groups explore the role of atomic-scale structure in surface processes and the formation of new compounds at interfaces. The *Contact Dynamics* group studies the multi-scale mechanisms underlying adhesion, friction and wear phenomena connected to applications in the EUV scanner, in particular at the reticle stage and the wafer table. The Nanophotochemistry group explores the working mechanisms of new classes of materials that can serve as photoresists in the EUV regime. In addition to the experimental research groups, the *Materials Theory and Modeling* group uses density functional theory (DFT) and other modeling techniques to investigate materials and surface properties in the context of EUVL. This combination of experimental and theoretical methods allows us to develop a comprehensive picture of nano- and micro-scale processes at interfaces in nanolithography, which is relevant for a wide variety of EUVL components, ranging from the optics to the wafer table.

Presenting Author

Roland Bliem received his PhD in 2016 from the Vienna University of Technology for work on the surface science of single-atom catalysts supported on iron oxides. He received an Erwin Schrödinger fellowship to support his postdoctoral position at the Massachusetts Institute of Technology, where he studied the effect of metal doping on the surface stability of energy materials. He is the group leader for Materials and Surface Science for EUV Lithography at the Advanced Research Center for Nanolithography and an Assistant Professor at the Institute of Physics of the University of Amsterdam since February 2019. His research interests include the effect of structural disorder on the surface stability of scanner materials and the surface chemistry of thin metal layers.

S83

ARCNL's Metrology Department: An Overview

Stefan Witte

ARCNL

The metrology department at ARCNL is dedicated to the development of novel light-based methods for precision measurements on nanolithographic devices. The aim of the department is to advance the possibilities that are available for e.g., wafer alignment, overlay metrology and at-resolution device inspection, both in terms of resolution and in dealing with complexities introduced by the device itself. The department consists of five research groups that focus on topics such as computational imaging, digital holographic microscopy, high-harmonic generation, photo-acoustics, ultrafast light-matter interaction and more. I will give an overview of the ongoing research in all groups and highlight the various links and application perspectives of the different research topics.

Presenting Author

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

Since 2014 he is a group leader in the EUV Generation and Imaging group at ARCNL and head of the Metrology Department and is associated with the Vrije Universiteit Amsterdam as an assistant professor. He was awarded an ERC Starting Grant in 2014, and an ERC Consolidator Grant in 2019. His present research interests include coherent diffractive imaging with visible and EUV radiation, high-harmonic generation and its applications, photo-acoustic imaging, and advanced laser development for plasma experiments.

S84

Introduction to ARCNL's Source Department

Oscar Versolato

Advanced Research Center for Nanolithography (ARCNL),
Science Park 102, Amsterdam

The Source Department at ARCNL is dedicated to obtaining fundamental understanding of the physical processes involved in each step in generating extreme ultraviolet (EUV) light. In this talk, I will give an overview of the research performed by the various groups in the department and their collaborators. The development of advanced solid laser systems in the *EUV Generation & Imaging* group will be discussed. Our brand-new *Plasma Theory & Modeling* group will be introduced. New results from the *Ion Interactions* group, part of the Source Department, will be presented. This group uses the specialized ion-beam facilities at Groningen University and is based there. Latest developments by the *EUV Plasma Processes* group will also be highlighted.

Presenting Author

Oscar Versolato received his PhD in 2011 from the University of Groningen, The Netherlands, related to 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). Since 2015 he is a tenure-track group leader in the EUV Plasma Processes group at the Advanced Research Center for Nanolithography (ARCNL) in 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. Oscar heads ARCNL's Source Department.

S85

Laser-driven Tin Plasma Expansion with Relevance to Extreme Ultraviolet Nanolithography

Diko Hemminga[1,2], Lucas Poirier[1,2], Mikhail Basko[3], Ronnie Hoekstra[1,4], Wim Ubachs[1,2], Oscar Versolato[1,2], John Sheil[1,2]

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State-of-the-art nanolithography machines employ extreme ultraviolet (EUV) light to pattern nanometre-scale features on silicon wafers for the production of integrated circuits. EUV light is produced efficiently in a laser-produced tin plasma from transitions in multiply charged tin ions. [1]

We will present a joint experimental and theoretical study of plasma expansion from Nd:YAG laser-irradiated (λ=1.064 μm) tin microdroplets. [2] Experimental measurements of the ion energy distribution exhibit a near plateau for ion energies in the range 0.03–1 keV, a localised peak at 2 keV followed by a sharp fall-off for energies above 2 keV. Charge-state resolved measurements disentangle this peak into the intersection of local maxima in the ion energy distributions of the tin ions Sn^{3+}-Sn^{8+}.

We have simulated the plasma formation and subsequent expansion using two-dimensional radiation hydrodynamic simulations based on a single-fluid hydrodynamic model. The resulting simulated ion energy distribution is found to be in good agreement with the experimental measurements both in terms of the shape of the distribution and the absolute number of detected ions. We attribute the aforementioned peak in the ion energy distribution to the presence of a quasi-spherical, high-velocity density shell formed during the early phase of the expansion.

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Presenting Author

Diko Hemminga is a PhD student in the EUV Plasma Processes group at the Advanced Research Center for Nanolithography and at the Vrije Universiteit in Amsterdam, the Netherlands. He puts into action radiation-hydrodynamics simulations of laser-produced plasmas on tin microdroplets. In collaboration with experimentalists and theorists he works on topics such as plasma expansion and droplet dynamics.
Previously he has studied Mathematics and Physics at the Vrije Universiteit Amsterdam and he is a graduate in Theoretical Physics from the University of Amsterdam and the Vrije Universiteit Amsterdam.

S86

Fully-calibrated Sn LPP EUV source spectrum from 5.5 nm – 265 nm

James Byers

University of Twente, Netherlands

We present the fully-calibrated spectrum from 5.5 nm – 265 nm of a Nd:YAG laser produced plasma microdroplet-Sn EUV light source, under conditions relevant to EUV lithography. A transmission-grating spectrometer was used in conjunction with a series of filters (Zr, Si, Al, LiF, MgF2, UVFS) to measure the 1st diffraction order spectrum without contamination from higher diffraction orders. A SiC 4-bounds mirror system was used to measure the otherwise inaccessible 40 – 100 nm range. The ability to characterize EUV sources from the soft-x-ray to the mid-UV region allows for the identification of prominent out-of-band emission regions, which can be used to optimize of EUV sources for lithography.

Presenting Author

James Byers received a B.Sc. in Physics and Philosophy from the University of Hull, UK, in 2013, an M.Sc. in Nanoscale Science and Technology from the University of Leeds, UK in 2015, and a Ph.D. in Si Photonics from the University of Southampton, UK, in 2020. During his Ph.D. he developed efficient Si photonic optoelectronic modulators for use in medium-range telecommunications, and on-chip polarization controllers, specializing in PhC design and nanofabrication. He is currently a postdoctoral researcher in the XUV Industrial Optics group at the University of Twente, NL, where he is working on spectroscopy and imaging of EUV light sources.

S88

Towards Energy Efficient Production of 13.5nm Light using 2µm Solid State Lasers

Yahia Mostafa

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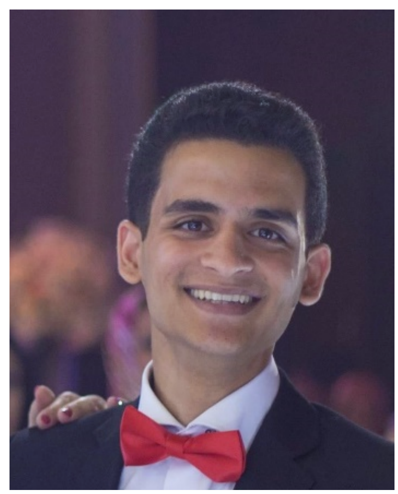
In our labs, a 2µm laser system is built with demonstrated variable pulse duration and shape. This 2µm laser is pulsed onto tin droplets, varying the laser pulse shape and duration to generate uniformly heated plasmas. This is shown to result in high laser light to EUV light conversion efficiencies. The high efficiency is due to the optimized optical depth of 2µm light. The laser light generates a thick and uniform plasma of the desired temperature to emit 13.5nm light. It is shown that the drive laser excites tin ions to multiple charge states which have a broad unresolved transition array at 13.5nm. This high conversion efficiency by 2µm drive laser may enable a high overall efficiency in converting electrical power to EUV light.

Presenting Author



Yahia is a PhD. Student at ARCNL investigate tin laser produced plasmas. The interests of his studies lie in understanding the mass ablation of liquid tin under irradiation by high-energy solid-state lasers. Further understanding of the ablation of tin will allow the control of the amount of emitting ions within plasmas, and in turn, mitigate the amount of debris is laser produced plasma EUV sources. Prior to his current position, Yahia obtained a BSc in physics at the University of Groningen. Following that, he completed a MSc. in Nanoscience at the same university.

S87

TI-REX: a 5->20ns Temporally Shapable and 1.4->4.4μm Wavelength-tunable Source for Nanolithography

Zeudi Mazzotta, Jan Mathijssen, Oscar Versolato, Kjeld Eikema, Stefan Witte

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Extreme Ultra-Violet (EUV) light, generated via laser-produced plasma (LPP), is now the tool for printing chips on nanometer scale. Currently 10.6μm CO_2 lasers are used, for their high demonstrated Conversion Efficiency (CE) from laser power to EUV. But in terms of laser technology, solid-state lasers have significant advantages in terms of efficiency, stability and control over temporal pulse shape and contrast. Moreover, CE studies for 1 and 2μm show that CE increases with wavelength [1,2], while simulations indicate that even further CE improvements can be expected towards λ=4μm [3].

Presently, no LPP-level laser architectures have been developed at drive wavelengths beyond 2 μm, thus no experimental data is available on CE scaling between 2μm and 10.6μm. Importantly, such CE investigations would require both sufficient pulse energy and a high degree of tunability in both wavelength and pulse duration. We are developing such a system, able to produce wavelengths in the range 1.45-4.5μm, which inherits high-resolution (~0.2ns) temporal shaping capability from our previously developed YAG laser [4], while providing sufficient energy and intensity for LPP. The "seed-free" aspect of the system and wavelength/temporal shape robustness of its architecture make this laser well-suited for a systematic CE measurement campaign.

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Presenting Author

Zeudi Mazzotta is a postdoc in the EUV Generation and Imaging group at ARCNL.

After her degree in Mathematics, she got a PhD position in physics in Milano, on an experiment on antimatter and gravity at CERN. Here she learned more about lasers, and especially about nonlinear optics, given the need of exciting a cloud of positronium atoms to Rydberg levels with a two-step excitation process: 1->3->Rydberg. She had then her first postdoc in Paris, on the European project EuPRAXIA, a design study of an industrial user-oriented laser-plasma electron accelerator.

Then she obtained the position at ARCNL on EUV source lasers: after inheriting the SNS laser [3] she is now finalizing the construction of the TI-REX laser, for new more systematic studies on SWIR/MID-IR wavelength-dependent CE behavior.

S89

Laser-vaporization of Tin Sheet Targets

Randy Meijer

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

We study the formation, fragmentation, and vaporization of tin targets for EUV sources. These targets are formed by laser impact on a microdroplet, which induces a propulsion and expansion of the droplet into a thin sheet. This sheet is bounded by a thicker rim from which ligaments form and fragments are expelled. The vaporization of such targets by a secondary laser pulse exposes the aforementioned distribution of the tin mass and creates a rapidly expanding vapor. We further explore the composition of the vapor and the laser-vaporization process.

Presenting Author

Randy Meijer is a postdoc researcher in the EUV Plasma Processes group at the Advanced Research Center for Nanolithography (ARCNL) in Amsterdam, The Netherlands. He obtained his master's degree in Physics at the University of Amsterdam with a project on nano-optomechanics and plasmonics at the NWO institute AMOLF. He then did his PhD research at ARCNL, where he developed an Nd:YAG laser system with arbitrary temporal pulse shaping capabilities and used this system to study laser-droplet interaction with a specific focus on the tunability of the laser pulse(s). His current research builds on his PhD experience and focusses on advanced target preparation for EUV sources.

S90

Fundamental Atomic-interaction Measurements: Single Electron Capture Cross Sections for Sn^{3+} on H_2 in the Energy Range 9-51 keV

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The Ionic Interactions group of ARCNL's Source department is situated at the University of Groningen, where we do precise measurements on the fundamental interactions of energetic Sn ions with both surfaces and gases. Modern EUV sources based on a laser-produced plasma (LPP) use hydrogen gas as a buffer gas to slow down the fast Sn ions coming from the LPP. Further optimization of this technique by simulations requires accurate atomic data on the energy loss and charge exchange processes in collisions of Sn ions of a specific energy and charge state with H_2 molecules. We have been working on generating this missing data at the ZERNIKELEIF facility where we can generate a beam of Sn ions of a pre-selected energy, charge state, and mass (isotope). We have obtained the single electron capture cross sections for Sn^{3+} on H_2 and on D_2 in the energy range 9-51 keV. At the lowest measurement energies large differences to the most advanced theoretical models are observed. Moreover, we find a substantial isotope effect which is not present in the theoretical models.

Presenting Author

Klaas Bijlsma studied Applied Physics at the University of Groningen in The Netherlands and obtained his MSc degree in 2019. His master's research project involved developing an ion mobility spectrometer for biomolecular ions. He carried out an internship at the National Institute of Standards and Technology in the United States, where he worked on the measurement of nanoscale spin dynamics in thin film materials. Since November 2019 he is a PhD student at the University of Groningen, in collaboration with the Advanced Research Center for Nanolithography (ARCNL). His research topic is the interaction of energetic tin ions with hydrogen gas.

S91

An Intense Soft X-ray Source driven by a Mid-IR OPCPA for Ultrafast Metrology in the Water-window

Zhonghui Nie

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High-harmonic generation (HHG) driven by femtosecond laser pulses has been demonstrated as a route to generate X-rays in a table-top beamline with high temporal resolution and coherence, which is crucial for scientific and industrial metrology. [1,2] Broadband X-ray sources could cover different absorption edges and allow for element sensitive investigations, and it also allows for high-resolution imaging of nanometer-sized structures. Although some attempts based on long wavelength have been reported to reach the water window,[3] low flux in present facilities still limits their practical applications. Thus, we propose to adopt a novel optical parametric chirped-pulse amplifier (OPCPA) to generate a soft X-ray source, where the mid-IR wavelength of ~2 μm ensures the full coverage of the water window, and the high repetition rate largely increases the photon flux. In this presentation, I will show the layout of such an intense X-ray source, including the laser system and discuss the main technical challenges and the corresponding designs. Furthermore, some outstanding parameters of our X-ray source will be demonstrated and ultrafast X-ray absorption in noble gas could be utilized to verify its capability for scientific research.

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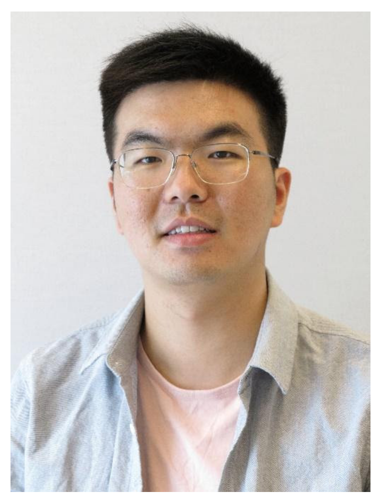

Presenting Author

Zhonghui Nie obtained his PhD at Nanjing University in 2019. He was responsible for the design and construction of the time-resolved angle-resolved photoelectron emission spectroscopy (TR-ARPES) system, based on high harmonic generation. Zhonghui subsequently continued ultrafast electronic and lattice dynamics of solids in Nanjing University of Science and Technology. Now he works at ARCNL since June 2021, to develop an intense and table-top soft X-ray source in the water window, driven by a mid-IR OPCPA, which could be applied for ultrafast spectroscopy and nanoscale metrology experiments with relevance to nanolithography.

S92

Tailoring Spatial Entropy in Extreme Ultraviolet Focused Beams for Multispectral Ptychography

Xiaomeng Liu, Lars Loetgering, Anne de Beurs, Mengqi Du, Patrick Konold, Kjeld Eikema, Stefan Witte

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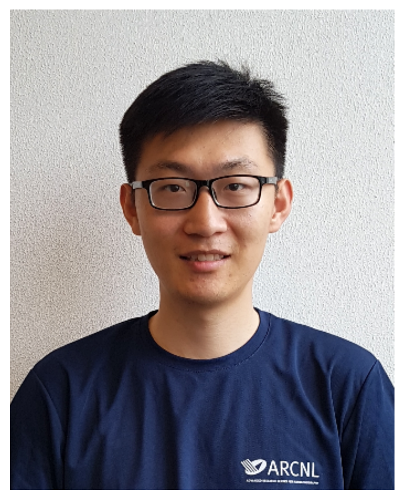
Department of Physics and Astronomy, and Laserlab, Vrije Universiteit, De Boelelaan 1081 HV Amsterdam, The Netherlands

We demonstrate a computational approach to designing diffractive optical elements (DOEs) that can be used to focus multispectral extreme-ultraviolet radiation from a high-harmonic generation source. We show that polychromatic focusing properties are experimentally confirmed using ptychography where up to 9 harmonic wavefronts are reconstructed simultaneously.

Presenting Author

Xiaomeng Liu is currently a Ph.D. student at the Advanced Research Center for Nanolithography (ARCNL) in Amsterdam, the Netherlands. He obtained his Bachelor of Science degree at Shandong university in China. Then he continued his study in the Netherlands and obtained his Master of Science degree at Groningen University with the thesis titled "Ultrafast exciton and charge dynamics in novel conjugated oligomers". He joined EUV Generation & Imaging group at ARCNL as a Ph.D. student under the supervision of dr. Stefan Witte and Prof. Dr. Kjeld Eikema. His current research focuses on high-harmonic generation of extreme-ultraviolet (EUV) in noble gas medium and exploring the boundary of broad band EUV lensless imaging.



S93

Lens Aberration Calibration and Correction in Digital Holographic Microscopy

Christos Messinis

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

Overlay metrology measures pattern placement between two layers in a semiconductor chip. In our group, we built a compact dark-field digital holographic microscope that uses a single imaging lens as an alternative optical overlay sensor that can address many of the existing metrology challenges. Such a sensor offers several features that are beneficial for metrology challenges, like a large wavelength range. However, imaging with a single lens results in highly aberrated images. In this talk, we will present an aberration calibration and correction method using nano-sized point scatterers to recover the full wavefront error and correct for lens aberrations. We will present measured data to verify the calibration method and demonstrate the correction on aberrated images of overlay targets.

References

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Presenting Author

Christos Messinis is a PhD employee at Advanced Research Center for Nanolithography (ARCNL) on the group of Computational Imaging under the supervision of Prof. Dr. Arie den Boef. The main goal of his research is the development of a metrology tool based on holography, capable of robust semiconductor metrology on a large wavelength range (400-1600 nm) with sub-nm precision. Christos holds a BSc on Material Science and a MSc on Photonics-Lasers both obtained from the University of Patras, Greece.

S94

Suppression of Hydrogen Blistering in Mo/Si Layered Structures

Victor Vollema

Advanced Research Center for Nanolithography,
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Hydrogen blistering is a well-known degradation mechanism that impacts fields from nuclear fusion, extreme ultraviolet lithography (EUVL) to even space engineering. The process involves the accumulation of hydrogen atoms inside a material, that recombine into hydrogen gas molecules to form subsurface gas pockets. These pockets cause delamination of the material above, showing as blisters on the surface. Recently, studies have explored this effect in Mo/Si multilayer structures, which are of considerable importance due to their use as Bragg mirrors in EUVL. However, the precise manner in which the hydrogen blisters nucleate is still under discussion, as are the exact conditions that are required for this to happen.

Here we show that deposition conditions can drastically affect the blistering behavior of a Mo/Si multilayer. We do this by fabricating a simplified Mo/Si layer structure under two different sets of deposition parameters and expose it to H_2^+ ions to induce hydrogen blistering. We observe that in one case the samples universally show blistering, while the other case does not show blistering at all. We propose a mechanism through which the blister nucleation occurs, that provides new insight into the hydrogen blistering process and possibly opens new pathways to eliminate such degradation altogether.

Presenting Author

Victor Vollema is 4th year PhD student at the Advanced Research Center for Nanolithography, in the Nanolayers group headed by Prof.dr. J.W.M. Frenken.

He pursued a Master's in Experimental Physics at the University of Leiden before joining ARCNL in 2017. His current work is centered around thin films in relation to EUV applications. Selected topics include the growth of thin metal films, as well as the interaction of thin film structures with hydrogen.