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Workshop Abstracts

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S1

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

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

Gigaphoton Inc. Hiratsuka facility: 3-25-1 Shinomiya Hiratsuka Kanagawa,254-8567, JAPAN

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

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3) Hakaru Mizoguchi, et al, "High Power HVM LPP-EUV Source with Long Collector Mirror Lifetime", EUVL Workshop 2017, (Berkley, 12-15, June, 2017)
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]

Presenting Author

Hakaru Mizoguchi is a Senior Fellow in Gigaphoton Inc., Fellow of The International Society of Optical Engineering (SPIE), and member of The Laser Society of Japan and The Japan Society of Applied Physics. He received a diplomat degree in plasma diagnostics field from the Kyushu university, Fukuoka, Japan in 1982 and join Komatsu ltd. He joined CO2 laser development program in Komatsu for 6 years. After that he was a guest scientist of Max-Plank Institute Bio-Physikalish-Chemie in Goettingen in Germany 2 years, from 1988 to 1990. Since 1990 he concentrated on KrF, ArF excimer laser and F2 laser research and development for lithography application. He was general manager of research division in Komatsu Ltd. until 1999. He got PhD degree in high power excimer laser field from Kyushu university in 1994. In 2000 Gigaphoton Inc. was founded. He was one of the founders of Gigaphoton Inc.. From 2002 to 2010 he organized EUV research group in EUVA program. Now he is promoting EUV light source product development with present position. He got Sakurai award from OITDA Japan in 2018.

S2

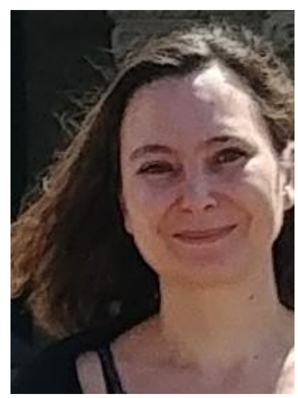
Source Performance Metrics for EUV Mask Inspection (Keynote Presentation)

Larissa Juschkin, Dan Wack, and James Westphal

KLA Corporation, One Technology Drive, Milpitas, 95035 CA, USA

We focus on the comprehensive overview of physical processes and technological aspects governing the requirements of radiation sources for actinic patterned mask inspection and metrology systems. These include ways of obtaining specs on radiance, power, lifetime, cleanliness, availability and stability of the source. We discuss differences and similarities to scanner with respect to magnification, system etendue, image recording, and monitoring irradiance. We depict the scaling laws for required radiance with targeted sensitivity index, optical contrast, field size, and system throughput. In addition, we address the limits on the required brightness and minimum repetition rate set by mask damage threshold and image capture statistics. Finally, system and source cleanliness requirements and criticality of the source availability and lifetime are discussed.

Presenting Author



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

S3

Evolving Source Demands and Requirements for EUV lithography in Manufacturing (Keynote Presentation)

Steve Carson

Intel Corporation

Extreme Ultraviolet lithography equipment is reaching a level of maturity that enables it to supplant 193nm-immersion as the leading-edge lithographic option. While challenges remain in ensuring sufficiently robust sources that are capable of supporting EUV lithography in high volume manufacturing, source power, power degradation, dose error performance, and source availability have shown tremendous improvements in recent years. As EUV lithography moves towards increased wafer throughput systems and high NA scanners, those same metrics (source power, power stability, dose error performance, and system availability) will require further improvements. In this presentation, the current achievements of EUV lithographic sources will be highlighted, the demands for future EUV sources will be explored, and potential requirements for those sources will be discussed.

Presenting Author

Steven L Carson is a Principal Engineer at Intel Corp. Steve joined the Photolithography department in Intel's Portland Technology Development organization in 1999 after completing a B.S. degree at the California Institute of Technology, and M.S. and Ph.D. degrees at the University of Florida, all in Chemical Engineering. He has been involved with developing stepper and scanner platforms from i-line to EUV for integration into high volume manufacturing. He has also been involved in the development of advanced process control (APC) applications and factory automation systems, earning patents in both. Since 2008, Steve has primarily focused on EUV imaging and its collateral technologies including the scanner, the source, EUV reticles, and EUV pellicle membranes.

S11

Ultrafast Extreme-ultraviolet Emission from Solids (Invited)

Peter Kraus

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

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 industrial applications of high-harmonic sources [3,4].Thus, both fundamental science and industrial applications now require more robust and brighter HHG sources, as well as a better understanding of the interaction of XUV photons with semiconductor wafers and thin films.

In this talk I will discuss new coherent all-solid extreme-ultraviolet high-harmonic sources, which might find applications in semiconductor wafer metrology. The recently discovered extreme-ultraviolet emission from solids opens an avenue to more compact HHG sources, and is a new method to study solids in high fields. I will discuss new experiments to boost the efficiency of XUV emission from solids through resonant enhancement in multi-color HHG, and ways to tailor the emission properties by engineering the surface of the materials.

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Presenting Author

Peter Kraus obtained his PhD at ETH Zurich (Switzerland) in 2015. He developed and advanced the techniques of high harmonic-spectroscopy for investigations of electronic and nuclear structure and dynamics of molecular systems. Peter subsequently worked at the University of California, Berkeley (USA) on the development of new experimental techniques for investigating attosecond phenomena in solid-state materials. He started as a tenure-track group leader/assistant professor at ARCNL in May 2018. Peter 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.

S12

Industrial kW-class Picosecond Thin-disk Lasers for EUV Light Sources (Invited)

M. Smrž, J. Mužík, M. Chyla, S. S. Nagisetty, P. Sikocinski, O. Novák, and T. Mocek

HiLASE Centre, Institute of Physics CAS,
Za Radnicí 828, 252 41 Dolní Břežany, Czechia

High-average-power sub-picosecond solid-state lasers are a versatile tool for hi-tech industrial processing and scientific applications. They are traditionally employed like pre-pulse systems in laser-produced plasma-based photon sources for EUV lithography. High-energy systems also serve as general sources of laser-produced-plasma emitting EUV and soft X-ray photons.

We present our progress in design and construction of commercial near- and mid-infrared thin disk laser technology extended by harmonic frequency generators to visible or UV spectral range, and by mid-IR extension up to wavelength of 4-um. Our laser platform called Perla reaches sub-kW average power, excellent beam quality (M^2 parameter as low as 1.1), and low output power fluctuations. Fully automated industrial version of the platform was lately demonstrated and is commercially available. 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, and optimization of high power Yb:YAG systems for multi-beam material processing.

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. His current research focuses on high average power sub-picosecond lasers and nonlinear optics for industrial and scientific applications.

S13

Ultrafast Thin-Disk Amplifiers (Invited)

Thomas Metzger

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

With an inexorable demand for increased average and peak power at the same time, the management of heat deposition and the buildup of nonlinearities have become pressingly challenging for energetic ultrafast lasers. Due to its efficient one-dimensional heat removal and the small longitudinal extension of the gain medium, the thin-disk geometry offers exceptional scaling performance both in terms of energy and average power. As a regenerative amplifier, 200 mJ were in fact recently extracted at 5 kHz out of two Yb:YAG disks [1,2]. A similar amplifier with an improved pulse duration of <500fs had been built at TRUMPF Scientific Lasers to demonstrate nonlinear pulse compression to pulse durations <50fs at nearly 2kW, 20kHz and 1kW, 5kHz respectively. Likewise, multipass arrangements have led to >1.9 kW with good temporal and spatial performances [3].

In this contribution, we present different commercial ultrafast solutions based on regenerative and multipass amplifiers with up to 0.5J and 0.7J respectively. Further nonlinear pulse compression experiments such as gas filled multipass cells [4] for various repetition rates and pulse energies are in preparation and the current status of the developments will be shown. Thus, combining both technologies, the completion of high-energy sub-50 fs lasers with multi-kW average output powers would be at our fingertips. Such laser sources could give rise to a manifold of exciting applications such as inverse Compton scattering [5], pumping optical parametric amplifiers [6], laser based lightning rod [7], high harmonic [8] and X-ray generation [9], laser wakefield accelerator-based light sources [10] and laser-driven neutron sources [11].

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Presenting Author

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

S14

A Laboratory Soft X-ray Microscope: Progress on a High Radiance Water Window Source for Imaging (Invited)

F. O'Reilly[1,2], W. Fyans[2], A. Boland[2], A. Manzoni[2], D.Rogers[2], J. Howard1,2, D. Skoko[2], M. Donnellan1,2, J. Costello[2], D. Hickey[2], I. Tobin[2], T. McEnroe[2], K. Fahy[2], P Sheridan[2]

[1]School of Physics, University College Dublin
[2]SiriusXT Ltd

The opportunity presented by soft x-ray microscopy is to use low wavelength photons for high spatial resolution imaging through relatively thick samples, with elemental contrast. These techniques have been developed at synchrotrons, but the main challenge in deploying sub 50 nm resolution microscopy more widely is the development of an affordable source that can deliver sufficient photons to a small sample volume. Here we will report on such a source working at 454 eV and demonstrate source performance and high-resolution microscope imaging data.

Presenting Author

S15

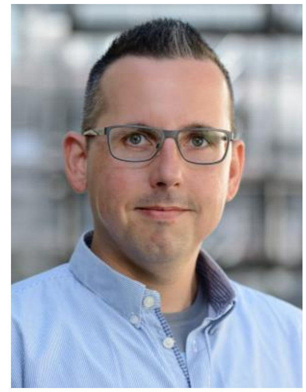
In-lab EUV Dual Beamline for Industrial and Scientific Applications

Sascha Brose[a,b], Bernhard Lüttgenau[a,b], Serhiy Danylyuk[c], Jochen Vieker[c], Klaus Bergmann[c], Jochen Stollenwerk[a,b,c], Peter Loosen[a,b,c]

[a] RWTH Aachen University, Chair for Technology of Optical Systems, Aachen, 52074, Germany
[b] JARA – Fundamentals of Future Information Technology, Jülich, 52428, Germany
[c] Fraunhofer Institute for Laser Technology, Aachen, 52074, Germany

In this contribution the authors present the design, realization and characterization of the in-lab EUV Dual Beamline used for advanced patterning processes in scientific and industrial applications. Depending on the application, the utilized discharge-produced plasma EUV source is operated either at an exposure wavelength of 10.9 nm or 13.5 nm. Large area patterning of nanoscale structures up to several cm^2 is carried out at an exposure wavelength of 10.9 nm by operating the source with an argon/xenon gas mixture without the need of spectral filtering. This results in an intensity of up to 2 mW/cm^2 in wafer plane and offers highest throughput of several mm^2/min. For the characterization of EUV photoresists at 13.5 nm wavelength, the source is operated with pure xenon. The initial broadband emission (7 nm to 17 nm) is filtered down to 13.5 nm in-band radiation by a customized multilayer mirror. For the partially coherent radiation the applied (achromatic) Talbot lithography has proven to be a valid interference scheme with demonstrated resolution of 28 nm and a theoretical resolution limit in the sub-10 nm regime. In addition to details on the source operation, the fabrication process of high-resolution phase-shifting transmission masks and latest exposure results are presented.

Presenting Author



Dr. Sascha Manuel Brose graduated in mechanical engineering in 2008 (University of Applied Science Aachen, Germany) and received the Ph.D. degree in mechanical engineering in 2019 from RWTH Aachen University. Since September 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 25 scientific publications mainly in the field of EUV lithography and metrology.

S21

Light source development for Mask and Wafer inspection HVM tools

Marco Weber and Reza Abhari

ETHZ

At ETH Zurich droplet-based laser produces plasma (LPP) light sources have been developed since 2007, with emphasis on high brightness inspections applications including wafer and patterned mask inspection. The research facilities demonstrated long run-time capabilities with continuous EUV brightness measurements of over 350 Wmm-2sr-1, fulfilling technical requirements of current and future mask and wafer inspection systems. By reducing the cost-of-ownership being a major driver for current and future research, a modular source with a small footprint has been developed, by optimizing subsystem components and standardizing interaction surfaces, allowing seamless integration into an inspection tool. Time resolved plasma plume measurements, of the high frequency light source will be presented and challenges for optimized source control are discussed. Updates concerning the newly built state of the art research facilities will also be presented.

Presenting Author

Marco M. Weber studied Mechanical Engineering at ETH Zurich in Switzerland. During his master thesis he worked on alternative actuation systems for liquid metal droplet dispensing systems used in laser produced plasma sources. Since 2015 he is a Doctoral Candidate at ETH Zurich in the Laboratory for Energy Conversion as part of the Applied Laser Plasma Science (ALPS) group. His main research focus lies in optimizing control parameters of plasma creation and evolution in the ALPS2 EUV light source research facility for industrial wafer and mask inspection applications.

S22

The EUV-Lamp: compact EUV source for actinic EUV metrology in laboratory and industry.

Rainer Lebert, Christoph Phiesel , Thomas Missalla , Andreas Biermanns-Föth

RI Research Instruments GmbH,
Friedrich-Ebert Strasse 75, 51429 Bergisch Gladbach

Extreme Ultraviolet lithography is used in production of cutting-edge ICs in growing numbers. While industrial focus is on the maturing of the scanners and HVM sources, flanking research and supply chain infrastructure was, is and will be a corner-stone for its development, ramp-up and sustainability. Hence, there is need for compact EUV sources for solving a variety of tasks in research, the supply chain quality control and in mask houses and fabs .

AIXUV made its EUV-Lamp, a Xe DPP EUV source, designed for providing access to the EUV photons in stand-alone experiments. These EUV-Lamp are now produced by RI Research Instruments. EUV-Lamps have been tailored to specific tasks in aspects of tool integration and spatial and spectral beam forming. Over the years many EUV-Lamps have been also used for a broad variety of applications, e.g., standalone actinic metrology tools, for the industrial qualification laboratory of EUVL components, in fusion research and space. We have also integrated the EUV-Lamp with specific optics, filtering, beam transport monitoring and detection for various applications. In this presentation, we will present the performance and applications of EUV lamp in various applications.

Presenting Author

Rainer Lebert graduated in physics at TH Darmstadt in 1984 and got his PhD from the RWTH Aachen in 1990. Short wavelength emission from dense plasmas has always been in his focus. While assistant professor at RWTH from 1994 - 2000, he supervised research on plasma spectroscopy and EUV emission from LPP and DPP plasmas. He has published more than 90 papers and filed more than 20 patents.

In September 2000 Dr. Rainer Lebert founded the AIXUV GmbH on EUV sources and industrial metrology for EUVL. In 2010 AIXUV assets were acquired into Bruker Advanced Supercon and later in 2015 into RI Research Instruments GmbH. Through his career he was leading groups working on lab-source based activities and tool developments as well as on femtosecond lasers and industrial optics. His role in RI now is senior expert supervisor and architect in early phases of tool and application developments.

S23

High-brightness LDP and LPP Sources for Metrology and Inspection Applications (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]

[1]BLV Licht- und Vakuumtechnik GmbH,
Steinbachstrasse 15, 52074 Aachen, Germany
[2]Fraunhofer ILT, Steinbachstrasse 15, 52074 Aachen, Germany
[3]Ushio Inc., 1-6-5 Marunouchi, Chiyoda-ku, Tokyo 100-8150, Japan

The Laser-assisted discharge-produced (LDP) plasma EUV source was developed as a light source for actinic mask inspection and beamline application. Since the focused laser irradiation is used to ignite the discharge, the LDP plasma has a unique feature of high brightness and high power. It can be operated at the frequency of up to 10 kHz generating >140 $W/mm^2/sr$ in-band EUV brightness after the debris filter. For the beamline application, the LDP source is typically operated at 3 kHz generating 70 $W/2\pi sr$ at the plasma. In the paper, the key performances of the source and the plasma dynamics of the LDP source will be discussed. The Laser-Produced-Plasma (LPP) source is also being developed at BLV Licht and Ushio aiming at the compact, high-brightness radiation source. A liquid tin-covered disk is used as a target and the laser irradiation intensity is adjusted to emit radiation at 13.5 nm. The experimental setup was upgraded in order to perform comprehensive experiments to further increase the source brightness by increasing the frequency as well as to address key development items. In the paper, the latest experimental results will be discussed including the source brightness scaling and fundamental data on EUV emission.

Presenting Author

Yusuke Teramoto received his 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 source development for NXE3100 scanner, especially in power scaling. Now he is working for BLV Licht- und Vakuumtechnik GmbH, an Ushio group company. He is currently the leader of R&D Unit 1 of EUV Business Project managed by Ushio Inc. and working on EUV and X-Ray metrology sources research and development.

S31

Energy Spectra of Suprathermal Gadolinium Ions for Beyond Extreme-ultraviolet Source

Hiromu Kawasaki,[1] Kyoya Anraku,[1] Yuto Nakayama,[1] Gerry O'Sullivan,[2] Atsushi Sunahara,[3] and Takeshi Higashiguchi[1]

[1]Department of Electrical and Electronic Engineering, Faculty of Engineering, Utsunomiya University, 7-1-2, Yoto, Utsunomiya, Tochigi 321-8585, Japan
[2]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
[3]Center for Materials Under Extreme Environment (CMUXE), School of Nuclear Engineering, Purdue University, West Lafayette, Indiana 47907, USA

Extreme-ultraviolet (EUV) lithography at 13.5 nm is expected to be introduced in high-volume manufacturing of integrated circuits (ICs). Lithography at this wavelength is capable of reaching feature sizes below 5 nm. Beyond that, switching to a shorter wavelength of around 6.5-6.7 nm, while maintaining or increasing throughput in the lithography system, would improve resolution by a further factor of two and extend. One of issues of the EUV sources is the debris mitigation. In the presentation we show the detailed energy spectra of suprathermal gadolinium ions for beyond extreme ultraviolet source around 6.7 nm.

Presenting Author

Hiromu Kawasaki 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.

S32

Development of Yb:YAG Thin-disk Regenerative Amplifier for Compact Plasma EUV Sources

Misaki Shoji,[1] Ryo Kageyama,[1] Juri Ogawa,[1] Gerry O'Sullivan,[2] Atsushi Sunahara,[3] Kazuyuki Sakaue,[4] Martin Smrz,[5] Tomas Mocek,[5] Taisuke Miura,[5] and Takeshi Higashiguchi[1]

[1]Department of Electrical and Electronic Engineering, Faculty of Engineering, Utsunomiya University, 7-1-2, Yoto, Utsunomiya, Tochigi 321-8585, Japan
[2]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
[3]Center for Materials Under Extreme Environment (CMUXE), School of Nuclear Engineering, Purdue University, West Lafayette, Indiana 47907, USA
[4]Photon Science Center, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-8656, Japan
[5]HiLASE Centre, Institute of Physics of the Czech Academy of Sciences, Za radnicí 828, 252 41, Dolní Břežany, Czech Republic

It is important to develop compact high repetition rate high brightness EUV source for the microscope and the absorption spectroscopy. According to a two-dimensional radiation hydrodynamic simulation in Sn plasma, the expected EUV source size was evaluated to be 16 micron by the sub-nanosecond laser pulse. The brightness would improve by the use of short pulse laser. Then we developed a high repetition rate, high average power Yb:YAG thin-disk regenerative amplifier. The average power was achieved to be 5 W at the repetition rates of 1 - 10 kHz at the pulse durations of 300 fs - 3 ps.

Presenting Author

Misaki Shoji is a graduate student in engineering at the Utsunomiya University. Her research activities have focused on the fiber laser, thin-disk regenrative amplifier, and supercontinuum vector beam generation.

S33

Stimulated Emission Depletion Phenomenon in Luminescence of Scintillator Excited by Soft x-ray toward High-resolution Water-window Microscope

Takeshi Higashiguchi,[1] Toshitaka Wakayama,[2] Misaki Shoji[1], and Takeo Ejima[3]

[1]Department of Electrical and Electronic Engineering, Faculty of Engineering, Utsunomiya University, 7-1-2, Yoto, Utsunomiya, Tochigi 321-8585, Japan
[2]School of Clinical Engineering, Saitama Medical University, 1397-1 Yamane, Hidaka, Saitama, 350-1241, Japan
[3]Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, 2-1-1 Katahira, Aoba-Ku, Sendai, 980-8577, Japan

Although imaging techniques using soft x-ray (SX) are being developed as the available photon flux increases because of the continuing development of synchrotron light sources, it will be necessary to downsize the pixel size of the SX camera to produce finer SX images. Application of the stimulated emission depletion (STED) method to a scintillator plate followed by use of this plate as a sensor is one promising method to reduce the pixel size of SX cameras. When the excitation light source changed to synchrotron radiation (SR) light with photon energy of 800 eV, the same STED phenomenon occurred. The spot size of the luminescence was reduced by the STED phenomenon and this spot size decreased as the STED laser's photon energy increased. The energy dependence of the Ce:LSO luminescence levels can be used to explain the change in the spot size at the luminescence point.

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.

S34

High-energy Features in the Ion-energy Distribution from Laser-produced Tin Plasmas

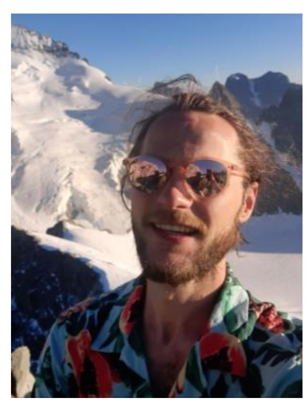
Lucas Poirier[1], Diko Hemminga[1], John Sheil[1], Adam Lassise[1], Ronnie Hoekstra[1,2], Wim Ubachs[1,3], Oscar Versolato[1,3]

[1]*Advanced Research Center for Nanolithography (ARCNL), Science Park 106, 1098 XG Amsterdam, the Netherlands*
[2]*Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, the Netherlands*
[3]*LaserLaB, Department of Physics and Astronomy, Vrije Universiteit, De Boelelaan 1081,1081 HV Amsterdam, the Netherlands*

In new-generation nanolithography machines, the patterning of nanometer-scale features is carried out by extreme ultraviolet (EUV) light produced in hot and dense tin droplet laser-produced plasma (LPP). However the expansion of tin LPP can be detrimental to the lifetime of the surrounding costly optics such as the main EUV collection mirror. Additionally, this plasma expansion in the EUV source vessel might impede the reproducibility of high EUV light yield at a fast repetition rate.

In this study we provide a further understanding of tin-plasma expansion and its most harmful aspects, namely the yield of highly energetic ions, in order to better design mitigation strategies. We cross-calibrate an electrostatic analyzer (ESA) with a Faraday cup (FC) in order to allow for the construction of charge-resolved energy spectra from tin LPP. A good agreement is reached between experimental ion energy spectra and their numerical counterpart, obtained from two-dimensional radiation-hydrodynamics simulations. In both instances the presence of a high-energy ion peak at supersonic speeds is ascertained. In the experiment charge state bunching at the high energy peak is observed consistently. By way of the RALEF-2D code, this noteworthy feature is shown to be a consequence of Gaussian temporal profile-driven plasma expansion at supersonic speeds, pointing to the hydrodynamic origin of the high-energy peak.

Presenting Author



Lucas Poirier graduated in Physics at l'*Ecole Normale Superieure* in Cachan, France. He first moved to the Netherlands to explore the use of inorganic perovskite nanocrystals in photovoltaics and LED research at the University of Amsterdam. In 2019, he became a doctoral student in the Advanced Research Center for Nanolithography in Amsterdam, with the objective to better characterize experimentally tin LPP expansion in a vacuum, and to design possible damage mitigation schemes.

S35

Interactions of Sn ions at Energies and In-charge States Relevant to the Mitigation of Sn ions coming from EUV Sources

S Rai[1,2], K I Bijlsma[1,2], S. Koeleman[1], W van Tellingen[1], B Schoonbeek[1], O O Versolato[2,3], R Hoekstra[1,2]

[1]Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands
[2]Advanced Research Centre for Nanolithography, Science Park 110, 1098 XG Amsterdam, The Netherlands
[3]Department of Physics and Astronomy, and LaserLaB, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands

Quantitative study of interactions of Sn ions with H_2 stopping gas and with plasma facing material (Mo, Ru) is important for optimizing Sn ion mitigation in LPP-EUV sources and for improving predictive capabilities of simulation codes.

At the ZERNIKELEIF facility in Groningen, mass, charge state, and energy selected Sn ions are generated by a 14 GHz supernanogan ECRIS and transported to setups dedicated for specific ion studies.

Experiments at H_2-gas-target setup investigate charge exchange, energy loss / stopping, and H_2 excitation and fragmentation. The setup, equipped with a faraday cup and a Time-of-Flight (ToF) mass spectrometer, is currently being calibrated using protons, for which charge exchange cross-sections are known. The integral hydrogen density acquired from these calibration measurements will subsequently be used to obtain the desired cross sections for Sn^{q+} ions on H_2. The data serves as a benchmark to stopping and charge-exchange codes.

At solid-target setup the scattering of ions off solid targets is studied by means of Low Energy Ion Scattering (LEIS) and ToF spectrometry. Our recent studies with Sn/Mo and Kr/Cu show discrepancy between experiments and SRIM in the single-collision feature of the energy spectra. First results obtained with the SDTRIMSP package will be presented.

Presenting Author

S41

Development Progress of the CO_2 Laser and Shooting Control System for the High Power LPP-EUV light source

Yuichi Nishimura, Yoshifumi Ueno, Takashi Suganuma, Yoshiaki Kurosawa, Takayuki Yabu, Georg Soumagne, Shinji Nagai, Tatsuya Yanagida, Yutaka Shiraishi, Kenichi Miyao, Hideyuki Hayashi, Yukio Watanabe, Tamotsu Abe, Hiroaki Nakarai and Hakaru Mizoguchi

Gigaphoton Inc. Hiratsuka Facility
3-25-1 Shinomiya Hiratsuka Kanagawa, 254-8555, JAPAN

Gigaphoton Inc. has been developing a CO_2-Sn-LPP EUV light source system which is the most promising high power 13.5nm light source solution for the manufacturing semiconductor patterns below 7nm. A major challenge of EUV light source consists in simultaneously achieving high power and long lifetime collector mirror. Hence a high-power CO_2 drive laser, an optimized target for high conversion efficiency plasma generation, an accurate droplet-laser shooting control system and an effective debris mitigation system are required. With our unique and original debris mitigation system using a magnetic field and a controlled chamber hydrogen gas flow, we have already demonstrated an actual collector mirror reflectivity degradation rate of -0.15%/billion pulses at an average power of 125W during a week operation[1]. To achieve more higher power operation, we developed new beam transfer systems for CO_2 laser and upgraded its amplifiers in cooperation with Mitsubishi Electric Corporation. In addition, we introduced highly precise shooting control system to stabilize the EUV emission on higher heat load conditions. Using these technologies, we achieved 365W (clean burst EUV power at I/F) in short-term operation and demonstrated 270W (clean burst EUV power at I/F) in mid-term at 100kHz repetition rate and 100% duty cycle operation.

Reference

[1] 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]

Presenting Author

S42

Thomson Scattering Diagnostics of EUV Source Plasmas and EUV Induced Hydrogen Plasmas (Invited)

Kentaro Tomita[1] and Kiichiro Uchino[2]

[1] Division of Quantum Science and Engineering, Graduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Kita-ku, Sapporo, Hokkaido 060-8628, JAPAN
[2] Interdisciplinary Graduate School of Engineering and Sciences, Kyushu University, 6-1, Kasugakoen, Kasuga, Fukuoka 816-8580, JAPAN

Thomson scattering (TS) measurements have been performed to clarify electron density (n_e) and electron temperature (T_e) of laser-produced tin plasmas for EUV lithography light sources1). In addition, we have tried to determine two-dimensional velocity field in the source plasmas. The velocity field was clarified by using Doppler shift of TS spectra. Results clearly showed that plasma flowed from a high-pressure region to a low-pressure region. TS was also performed to measure spatial profiles of n_e and T_e in hydrogen plasmas, which were induced by radiation from EUV source plasmas. In the experiment, the tin plasma was produced in hydrogen gas of pressure 50-400 Pa, which is practically used to defend EUV collector mirrors from high-energy tin ions and atoms. The range of measured n_e was 10^{16}-10^{18} m^{-3}.

Reference

1) K. Tomita *et al*., "Time-resolved two-dimensional profiles of electron density and temperature of laser-produced tin plasmas for extreme-ultraviolet lithography light sources", *Sci. Rep*. **7** 12328 (2017)

Presenting Author

Kentaro Tomita is an Associate Professor in the Hokkaido Univ. He is member of The laser Society of Japan, The Japan Society of Applied Physics, and The Japan Society of Plasma Science and Nuclear Fusion Research. He received B. S., M. S., and Ph. D. degrees from Kyushu University, Japan, in 2002, 2004, and 2014, respectively. In November 2006 he was appointed Research associate at Kyushu University and became Assistant Professor in April 2007 at the same university. He became Associate professor in July 2020 at Hokkaido University, Japan. He is engaged in research of laser-aided diagnostics of industrial plasmas such as laser produced plasma for extreme ultra-violet light sources, atmospheric-pressure non-equilibrium plasma, arc discharge plasma, etc., which are produced under high pressure.

S43

Feature of Highly-charged Suprathermal ions from Laser-produced Plasma EUV Sources (Invited)

Takeshi Higashiguchi

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

We investigated the charge-separated spectra of highly charged suprathermal tin (Sn) and gadolinium (Gd) ions from the laser-produced plasma EUV sources and bismuth (Bi) ions for water-window soft x-ray source. The charge distribution of these suprathermal ions emitted from a solid planar Sn, Gd, and Bi targets was measured by an electrostatic energy analyzer (ESA). This evaluation provides important information essential for the development of debris mitigation schemes in the clean laser-produced plasma light sources.

Presenting Author

Takeshi Higashiguchi is a professor in the Utsunomiya University. 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.

S44

2020 Source Workshop Invited Presentation (Tentative title)

Michael Purvis

ASML

Presenting Author

S45

Physics Aspects of Solid-state-laser-driven Plasma Sources of EUV light: ARCNL's Source Research program (Invited)

Oscar Versolato

ARCNL

The Source Department at ARCNL is dedicated to contributing to the understanding of the physical processes involved in generating extreme ultraviolet (EUV) light, at the fundamental atomic level. I will give an overview of the research performed by the groups in our Source Department and present some notable highlights such as the improved understanding of the true origins of EUV light, new results of plasma driven by 2-micron laser light, as well as new insights obtained into the fluid dynamics of droplet deformation upon laser-pulse impact.

Presenting Author

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

S46

Interactions of Tin Ions in and Around LPP-EUV sources (Invited)

Ronnie Hoekstra[1,2], Lars Behnke[1], Klaas Bijlsma[1,2], Zoi Bouza[1], Diko Hemminga[1,3], Harry Jonkman[2], Sybren Koeleman[2], Adam Lasisse[1], Lucas Poirier[1], Subam Rai[1,2], Joris Scheers[1,3], Ruben Schupp[1,3], John Sheil[1], Wouter van Tellingen[2], Francesco Torretti[1,3], Wim Ubachs[1,3], Oscar Versolato[1]

[1]Advanced Research Center for Nanolithography (ARCNL), Amsterdam, the Netherlands
[2]Zernike Institute for Advanced Materials, University of Groningen, Groningen, the Netherlands
[3]Department of Physics and Astronomy and LaserLaB, Vrije Universiteit, Amsterdam, the Netherlands

In this talk our progress on identifying and characterizing multiply charged tin ions, charge state and kinetic energy, and their interactions with stopping gas and plasma-facing materials surrounding a laser-produced plasma (LPP) extreme ultraviolet (EUV) light source is presented. The following topics will be addressed:

• EUV line identifications in Sn^{q+} ions in the 10 – 20 nm combining plasma observations with charge state resolved spectra from an electron beam ion trap (EBIT).
• Time- and space-resolved optical Stark spectroscopy in the afterglow of the LPP plasma.
• Cross calibration of ESA-ToF and Faraday Cup measurements of ions coming from the LPP droplet source.
• Sn ion interactions with solid material (Ru, Mo) towards improvement of the predictive power of the commonly used SRIM simulation package.
• Aspects of stopping and charge exchange interactions of Sn ions traversing H_2 gas.

Presenting Author

S47

The Opacity of Sn at Conditions Relevant to CO_2 Laser-produced Plasmas (Invited)

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

[1]*Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[2]*Advanced Research Center for Nanolithography, Science Park 106, 1098 XG Amsterdam, The Netherlands*

Recent work by us has uncovered the importance of multiply excited states to the EUV emission spectrum of Sn plasma [1]. It was found that, for Sn plasmas created by Nd:YAG lasers, transitions from the ground manifold contributed around 10% to the total opacity, with 90% arising from transitions involving multiply excited states. The critical electron density of such plasmas was of the order of ^{1021} cm^{-3}.

We have recently analyzed the EUV emission arising from lower density Sn plasmas at conditions relevant to CO_2 laser-produced plasmas. At lower densities, the contribution from excited states might be thought to diminish. Also, the assumption of local-thermodynamic-equilibrium (LTE), which we have made in all our opacity calculations so far, may not hold at the lower density conditions. In this talk we explore both of these questions by analyzing calculations made using the Los Alamos ATOMIC code [2,3]. ATOMIC has been used to calculate opacity tables under the assumption of LTE, but can also be used in a non-LTE mode. Our plasma kinetics calculations utilize atomic structure and transition data from the Los Alamos suite of atomic physics codes [4,5].

[1] F. Torretti, J. Sheil, R. Schupp, M. M. Basko, M. Bayraktar, R. A. Meijer,S. Witte, W. Ubachs, R. Hoekstra, O. O. Versolato, A. J. Neukirch and J. Colgan, Nature Communications 11, 2334 (2020).
[2] N. H. Magee, J. Abdallah, J. Colgan, P. Hakel, D. P. Kilcrease, S. Mazevet, M. Sherrill, C. Fontes, and H. L. Zhang, Atomic Processes in Plasmas, 14th APS Topical Conference Proceedings, (Eds.: J. S. Cohen, S. Mazevet, and D. P. Kilcrease), Santa Fe, NM pp 168-180 (2004).
[3] P. Hakel, M. E. Sherrill, S. Mazevet, J. Abdallah Jr., J. Colgan, D. P. Kilcrease, N. H. Magee, C. J. Fontes, and H. L. Zhang,11th International Workshop on Radiative Properties of Hot Dense Matter, J. Quant. Spectr. Rad. Transfer 9, 265 (2006).
[4] C. J. Fontes, H. L. Zhang, J. Abdallah Jr, R. E. H. Clark, D. P. Kilcrease, J. Colgan, R. T. Cunningham, P. Hakel, N. H. Magee and M. E. Sherrill, J. Phys.B 48, 144014 (2015).
[5] R. D. Cowan, The Theory of Atomic Structure and Spectra (University of California Press, 1981).

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Presenting Author

James Colgan is the group leader of the Physics and Chemistry of Materials group at Los Alamos National Laboratory, New Mexico, USA. He has spent much of his career in the fields of atomic & plasma physics, and recently worked on the production of a new generation of opacity tables for the elements hydrogen through zinc. Such tables are used for a variety of programmatic and astrophysical modeling purposes. James has broad interests in atomic structure and atomic collision physics, atomic processes in plasmas, and modeling a variety of laser-produced plasmas.

S48

The Morphology of Liquid-tin Sheet Targets

B. Liu,[1, 2] R. Meijer,[1, 2] J. Hernandez-Rueda,[1] D. Kurilovich,[3] Z. Mazzotta,[1] S. Witte,[1, 2] and O. O.Versolato[1, 2]

[1-] *Advanced Research Center for Nanolithography (ARCNL), Science Park*
[2-] *LaserLab, Vrije Universiteit Amsterdam*
[3-] *ASML, Veldhoven*

We study the expansion dynamics of liquid tin microdroplets stretching to a sheet upon ns-laser irradiation using dual-color stroboscopic shadowgraphy. Features including the sheet thickness and the mass distribution have been independently investigated by using, first, partial transparency from the target sheet, and second, a laser-induced tin disintegration on the sheet. Particularly, in the latter measurement we employ a double laser pulse sequence in order to first deform a tin droplet and subsequently, disintegrate it into a mist of small particles that expands violently. Besides the sheet morphology, we studied the speed and the size of the fragmenting debris from the sheet using the time-resolve imaging system. The overall goal of our study is to gain insight into the fluid dynamics and disintegration mechanisms using experimental conditions relevant to extreme ultraviolet light generation for nanolithography.

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. These studies further inspire the optimization of the tin utilization in the source chamber of EUV-based nanolithography machines.

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 group of EUV Plasma Processes 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.

S51

Present Status of cERL-FEL as a Proof of Concept on the EUV-FEL High-power Light Source for Future Lithography (Invited)

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

High Energy Accelerator Research Organization (KEK)

In order to realize the 3 nm node and beyond, it is expected to be necessary to develop a high-power EUV light source of 1kW or more. To this end, an energy recovery linac (ERL)-based free-electron laser (FEL) are the most promising candidate, so that some feasibility studies on the accelerator technology has been conducted[1)]. In order to realize the EUV-FEL high-power light source, it is also important to reduce the size of the EUV-FEL system, so that several items for accelerator technologies were discussed at the previous symposium[2)]. One of the important milestones is actually demonstrating high-repetition rate ERL based FEL light production regardless of FEL wavelength. At the previous workshop, the Mid-Infrared FEL (MIR-FEL) construction in our compact ERL (cERL), whose electron beam energy is about 17 MeV, has been presented[3)]. Even at the mid-infrared light sources, there is no such high-repetition rate and high-power light source without a mirror system, in which the wavelength is tunable. In November 2019, the previous accelerator lattice components were removed in order to install two undulators to produce FEL light, and these were installed on the site at the middle of January and middle of April 2020, respectively. A preliminary commission of the cERL-FEL operation is progressing now. The first light of MIR radiation was observed at March from first undulator, and also from the second undulator at June. The radiation has a big enhancement of the intensity according to the bunch compression, so that the radiation is not a normal spontaneous emission. At the workshop, we will present the latest results and discussions about the obtained results as the POC on the high power EUV-FEL for future lithography.

1) "Strategy to realize the EUV-FEL high power light source - Present status on the EUV-FEL R&D activities –", H. Kawata, International Symposium on Extreme Ultraviolet Lithography, Hiroshima (2016).
2) "Challenges to realize the EUV-FEL high power light source for HVM system", H. Kawata et.al, Photomask Technology + EUV Lithography, Monterey (2017).
3) "Development to realize the EUV-FEL high power light source for future lithography", R. Kato et.al, 2019 Source Workshop, Amsterdam (2019).

Presenting Author

Hiroshi Kawata obtained his doctorate at the Tokyo Institute of Technology in a study of the surface state on the ferroelectric using X-ray diffraction method in 1982. In 1982, he became an assistant to Toyama University and in 1983 he moved to the Photon Factory in KEK and contributed to the research by X-ray diffraction, absorption and inelastic scattering based on synchrotron radiation.

He became an associate professor in 1992 and a professor in 2000 in KEK. From 2006, he was a project leader of KEK's future light source ERL (Energy Recovery Linac) project and since 2014 he has contributed to the development of EUV-FEL light source design work using ERL accelerator technology. He is now a honorary professor in KEK and also a researcher belonging to Center for Applied Superconducting Accelerator in KEK.

S52

High-power EUV Light Source Based on Steady-state Microbunching Mechanism

Xiujie Deng

The SSMB Collaboration

Steady-state microbunching (SSMB) in an electron storage ring promises EUV radiation with high-average-power (kW), high-repetition-rate (MHz to CW) and narrow-linewidth (<2%), which could be a candidate addressing the need of high-power EUV source for the high volume manufacturing of EUV lithography. An initial task force has been established at Tsinghua University, in collaboration with researchers from China, Germany, the USA, and elsewhere, to promote SSMB research with the goal of developing an EUV SSMB storage ring. In this talk, the main tasks of the collaboration at this moment, which consist of proving the SSMB working mechanism, the dedicated magnet lattice design for EUV SSMB storage ring and the efforts to address related technical challenges, are presented. The recent important progresses of the collaboration are highlighted.

Presenting Author

Xiujie Deng is an accelerator physics Ph.D. student at Tsinghua University, Beijing, China. He received the B.S. degree from Tsinghua University in 2015. His current work focuses on the physics of a novel accelerator light source concept called steady-state microbunching (SSMB).

S53

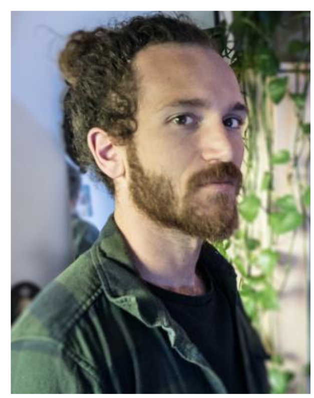
7nm and below: A Study for Undulators as an EUV Source

Thomas Grandsaert[1], Hamed Tarawneh[2], Sverker Werin[1],
Andrey Shavorskiy[2]

[1]*Lund University, Sweden*
[2]*MAX IV Institute, Lund, Sweden*

To move to lower modes in EUV lithography technology (and keep up with Moore's law), new sources of radiation must be developed. It is clear from previous studies that Free Electron Lasers (FELs) can easily meet the in-band power requirements at these lower wavelength modes, however detailed studies for insertion devices (undulators) as a soft X-ray lithography source are due for a re-evaluation. Here we present the results of a systemic study to determine the undulator parameters to meet the required dosage, while meeting typical optical characteristics for wafer stages. To do this we resolved a large parameter set to find maximum in-band power at each wavelength mode. Using the resolved undulator parameters we could develop an accelerator lattice to further realize the conceptual footprint of such a machine. Finally, we made a proposal for post-processing components which could achieve reasonable optical characteristics like numerical aperture, depth of focus and power density.

Presenting Author



Thomas is an engineer and physics master's student at Lund University who has worked in the accelerator field for 10 years. Previously holding a position at Radiabeam Technologies and currently at the European Spallation Source, his interests include accelerators, engineering and optics.

S54

Characterization of Tin plasma Driven by High-energy, 2-µm-Wavelength Light

Lars Behnke[1], Ruben Schupp[1], Adam Lassise[1], Zoi Bouza[1], John Sheil[1], Muharrem Bayraktar[3], Ronnie Hoekstra[1,4], Wim Ubachs[1,2], Oscar Versolato[1,2]

[1]*Advanced Research Center for Nanolithography (ARCNL), Science Park 106, 1098 XG Amsterdam, The Netherlands*
[2]*Department of Physics and Astronomy, LaserLaB, Vrije Universiteit Amsterdam, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*
[3]*Industrial Focus Group XUV Optics, MESA+ Institute for Nanotechnology, University of Twente, Drienerlolaan 5, 7522 NB Enschede, The Netherlands*
[4]*Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*

Extreme ultraviolet (EUV) lithography has recently successfully entered high-volume manufacturing. The light for this lithography process origins from 4d-4f, 4d-5p and 4p-4d electronic dipole transitions in highly charged Sn^{8+}- Sn^{14+} ions, produced by irradiation of tin microdroplets by high-intensity 10-µm wavelength pulses from CO_2 gas lasers [1,2]. For future lithography applications it is of interest to further optimize these plasma light sources regarding their energy efficiency and footprint. Here recent modeling work has highlighted the possible improvements regarding said parameters when using high-power, solid-state-based 2-µm drive laser systems that might soon become available. This 2-µm drive wavelength is situated between the well-studied cases of 1- and 10-µm, and is expected to combine the advantages of a more efficient absorption of laser light by the plasma compared to the 10-µm laser case, with a smaller optical depth and, thus, better spectral purity than in the 1-µm laser case [3,4].

We present experimental results from tin plasmas driven by high-energy pulses of 2-µm wavelength light, produced by an in-house built KTP-based master oscillator power amplifier (MOPA) system. The so produced plasma is then characterized regarding key performance indicators of spectral purity, conversion efficiency as well as its spectral emission. Further, the role of optical thickness in the plasma is discussed.

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[3] R. Schupp, et al. "Radiation transport and scaling of optical depth in Nd:YAG laser-produced microdroplet-tin plasma." *Appl. Phys. Lett.* 115(12) 124101 (2019)
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Presenting Author

Lars Behnke studied Physics at the RWTH Aachen in Germany. During his master program he focused on the fields of laser physics, optics and EUV related topics. In 2018 he graduated by writing his master thesis about a fundamental investigation of a gas-discharge driven EUV-Laser. Since the beginning of 2019 he is a PhD-student at ARCNL. He performs his current research about EUV plasma sources in the EUV Plasma Processes group of Dr. Oscar Versolato, Prof. Ronnie Hoekstra and Prof. Wim Ubachs.

S55

Angular and Spectral Bandwidth of XUV Multilayers Near Spacer Material Absorption Edges (Invited)

A. A. Zameshin, A.E. Yakshin, F. Bijkerk

University of Twente

High resolution imaging systems for XUV range are based on multilayer optics. Current generation of XUV lithography uses broadband Sn LPP sources that need broadband optics. Still, there remains a possibility to use FEL or synchrotron as XUV source. FEL can produce bright narrowband XUV light of a tunable wavelength, and the spectral bandwidth of the mirror is no longer a limitation. However, for large aperture XUV optical systems it is still important to know what happens to the angular bandwidth (angular acceptance) at lower wavelengths. It is usually assumed to be proportional to the spectral bandwidth. We show that on the contrary, the angular bandwidth of several multilayer systems can in fact increase, opposite to what occurs with the spectral bandwidth. We determine that this is caused by an interplay of changing optical constants of the used materials. We also provide an experimental check for Mo/Si multilayers at 13.5 and 12.6 nm, which confirms our calculations.

This talk is based on the following publications:

- A.A. Zameshin, A.E. Yakshin, A. Chandrasekaran, F. Bijkerk, "Angular and spectral bandwidth of Extreme UV multilayers near spacer material absorption edges", Journal of Nanoscience and Nanotechnology 19, 602-608 (2019).
- D. S. Kuznetsov, A. E. Yakshin, J. M. Sturm, R. W. E. van de Kruijs, E. Louis, and F. Bijkerk, "High-reflectance La/B-based multilayer mirror for 6x nm wavelength", Optics Letters 40, 3778 (2015).

Presenting Author

Dr. A. Zameshin is a postdoctoral researcher at XUV Optics Group, MESA+ Institute of Nanotechnology, University of Twente, in The Netherlands.

S62

Imaging of Integrated Circuits using 3D X-ray Ptychography

Mirko Holler

PSI

High-resolution imaging of integrated circuits (IC’s) is important for today’s information technology. It provides the microscopic starting point for the optimization of production and design, as well as for failure analysis. Standard procedures for device-level inspection of IC’s are destructive and require delayering. We demonstrate that ptychographic X-ray 3D imaging can be an alternative, non-destructive solution, with various advantages compared to established methods.

X-ray ptychography is an imaging method combining coherent diffractive imaging and scanning microscopy. The high penetrating power of multi-keV X-rays allows the non-destructive imaging of thick objects, while lens-less imaging at a coherent synchrotron source with state-of-the-art instrumentation provides unprecedented resolution. Combined with computed tomography it provides quantitative 3D information. Ptychographic 3D X-ray imaging is applicable to many science problems ranging from materials science to biology. In the case of IC’s it permits the non-destructive inspection of the interconnect structures down to the transistor level.

Presenting Author

S63

EUV Mask Inspection with the RESCAN APMI Tool: Effects of the Illumination NA

R. Nebling, H.-S. Kim, A. Dejkameh, T. Shen, Y. Ekinci and I. Mochi

Paul Scherrer Institute, Villigen, Switzerland

RESCAN is an APMI microscope prototype developed at the Paul Scherrer Institute. We use coherent EUV light from the Swiss Light Source synchrotron to perform coherent diffraction imaging on EUV reticles and detect defects on the mask surface. RESCAN is based on ptychography, a technique where the sample is scanned by a spatially confined illumination probe in overlapping positions. From the collected relative diffraction patterns, an image of the mask is computationally reconstructed using a phase-retrieval algorithm.

The theoretical imaging resolution of the RESCAN tool is 37 nm and the illumination NA ranges from 0.002 to 0.02. We demonstrated the detection of amplitude and phase defects down to 50 x 50 nm^2, and successfully shown through pellicle imaging.

We are currently upgrading our tool with a Fourier synthesis illuminator that will allow for a maximum synthetic imaging NA of 0.24. This enhances the resolution down to 20 nm on mask, or 5 nm on wafer, and enables defect detection for current and future technology nodes. In the new RESCAN setup, the illumination NA is increased to a value of 0.035. We studied in simulation the effects of the illumination NA on EUV mask inspection with coherent diffraction imaging on the image quality and the subsequent defect detection.
In this talk, we will introduce our RESCAN APMI microscope and discuss the effects of the illumination NA on EUV mask inspection with coherent diffraction imaging.

Presenting Author

Ricarda Nebling joined the Paul Scherrer Institut in 2018 as a PhD student, where she is working on the development of RESCAN, an actinic patterned mask inspection platform for EUV lithography. Within the RESCAN project, her focus lies on the image reconstruction procedure using phase retrieval algorithms. She has received her bachelor's degree in Materials Science and her master's degree in Micro and Nanosystems from the Swiss Federal Institute of Technologies in Zurich (ETHZ).

S64

Toward High-resolution and Efficient Reconstruction for EUV Actinic Mask Review

H. Kim[1], U. Locans[1], A. Dejkameh[1,2], R. Nebling[1,2], T. Shen[1,2] , D. Kazazis[1], Y. Ekinci[1] and I. Mochi[1]

[1]Paul Scherrer Institute, Switzerland
[2]Eidgenössische Technische Hochschule (ETH), Switzerland

Accurate metrology of EUV (Extreme Ultraviolet) reticles, from the mask production to the delivery on to the lithography process, is a crucial requirement in EUV lithography. In this work, we explore the possibility of carrying out mask metrology with a lensless imaging approach based on coherent diffractive imaging (CDI) as a promising technology for actinic pattern mask inspection (APMI) and review.

RESCAN (Reflective mode EUV scanning microscope) is a CDI-based APMI platform built at the Swiss Light Source synchrotron. We have already presented APMI with a resolution down to 50 nm for phase and amplitude defects. We also studied conical diffraction correction for the enhancement of resolution and the field of view in the current system.

RESCAN is currently undergoing an upgrade to include flexible illumination pupil capabilities to increase the resolution of the optical system and to emulate the aerial image of the mask under different illumination configurations.
In this talk, we will show the results obtained with the current version of RESCAN and discuss about the future projects.

Presenting Author

S65

Image Blur Measurement using EUV Interference Lithography for the Characterization of Resist and Exposure tools Performances

T. Allenet[a], J. G. Santaclara[b], G. Rispens[b], B. Geh[c,d], Y. Ekinci[a]

[a] Laboratory for Micro- and Nanotechnology, Paul Scherrer Institut, 5232 Villigen-PSI, Switzerland
[b] ASML, De Run 6501, 5504 DR Veldhoven, The Netherlands
[c] Carl Zeiss SMT, Rudolf-Eber-Straße 2, 73447 Oberkochen, Germany
[d] ASML TDC, 399 W. Trimble Road, San Jose, CA 95131, USA

As we move towards the deployment of high-NA EUV lithography, photoresist development continues to be one of the most prominent challenges to reach yet sharper resolutions. In this work we investigate image blur in order to assist the push towards sub-10 nm feature dimensions. Image blur comes from the convolution of both the aerial image blur induced by the exposure tool (mechanical stability and optical aberrations) and the latent image blur in the resist (photo-chemical reactions and diffusion). In this work we investigate resist exposure latitude (EL) as well as line-width roughness through pitch to determine current resolution limits. Different resist platforms are compared in an attempt to de-correlate limitations in resist chemical mechanism from limitations in an exposure tool. The method used here is based on the experimental analysis of dense lines/spaces.

For this work, the EUV-Interference Lithography (IL) tool at Paul Scherrer Institute (PSI) is used as an alternative to EUV scanners for resist screening. In IL the aerial image of lines/spaces is generated by the interference pattern of two plane waves which allows for a constant, pitch and depth of focus independent contrast. Two-beam transmission diffraction grating masks are fabricated by patterning hydrogen silsesquioxane spin-coated on 100 nm thick silicon nitride membranes thanks to e-beam lithography. Results are obtained with 13.5 nm exposures at the PSI beamline, SEM imaging and in-house software image analysis. The measurement of resist contrast through pitch allows the extraction of the image blur. Further characterization of resist parameters using the k4 metric are used to ultimately characterize tool performances.

Presenting Author

S66

Chemically Amplified Backbone Breaking Polymers: Designing New Resists for EUV lithography

Theodoros Manouras, Dimitris Kazazis, Yasin Ekinci

Paul Scherrer Institute

The continuous need for dimensional shrinkage in integrated circuits and the expansion of applications in the broader field of micro and nanosystems lead to the quest for new lithographic technologies capable of addressing the demands of the high-volume manufacturing (HVM). In this context, extreme UV lithography (EUVL) at a wavelength of 13.5 nm is the leading technology for the current node. The well-known trade-off in optimizing sensitivity, roughness, and resolution (RLS) continues to pose immense challenges towards future technology nodes, which require high-performance photoresists with high sensitivity (<20mJ/cm^2) to secure reasonably high scanner throughput. Until now, chemically amplified resists (CARs) have been used in EUVL since they have the advantage of compatibility with mature manufacturing. Still, several issues, such as low sensitivity, photon shot noise, and LWR, need substantial further improvement. On the other hand, metal-containing resists have attracted a lot of attention in recent years but are not yet as sensitive as desired.

In this paper, we report on the development of new polymeric materials for lithographic applications. The core concept of this new platform (Chemically-amplified backbone scission (CABS) resist) is based on the scission of the main polymer chain under the influence of photogenerated acid. This type of material is, in principle, capable of creating nanoscale structures, to the dimensions of the monomers that they consist of. Nevertheless, in the case of the commonly used non-chemically amplified materials of this type, issues like sensitivity and poor etch resistance limit their areas of application, whereas inadequate etch resistance and unsatisfactory process reliability are the usual problems encountered in acid-catalyzed materials based on main chain scission. In our material design, the acid-catalyzed chain cleavable polymers contain very sensitive moieties in their backbone while they remain intact in alkaline ambient. They bear, in addition, suitable functional groups for the achievement of desirable lithographic characteristics. We chose to introduce polyaromatic hydrocarbons in the polymeric backbone to achieve increased etch resistance and other functional groups for good solubility and adhesion to the substrate. Single component systems can also be designed following this approach by the incorporation of suitable PAGs and base quencher molecules in the main chain.

The polymers that will be presented have been evaluated so far as components of chemically amplified resist formulations exposed to EUV radiation (at 13.4 nm). The imaging chemistries have been investigated using spectroscopic techniques. A characteristic contrast curve shows that the resists are ultra-high sensitive (0.5 mJ/cm^2) using 5% PAG and 5% quencher with good contrast. In addition, they showed excellent etch resistance, similar to commercially available Novolac photoresists. Imaging experiments using EUV interference lithography have demonstrated capability for 22 nm hp with a dose of 10 mJ/cm^2 using 3 % PAG and 3% quencher with respect to the polymer and the PAG weight, respectively. We believe that this newly-developed material platform has a lot of room for improvement and further development will involve resolution and sensitivity optimization and absorption enhancement towards the targeted RLS specifications for high-NA lithography.

Presenting Author

S67

Preliminary Design Considerations for an Electron Storage Ring with Application to EUV Mask Inspection

T. Garvey, A. Streun, Y. Ekinci

Paul Scherrer Institut

The design of a compact synchrotron light source for the production of EUV radiation for metrology applications in the semiconductor industry is presented. Stable, high brightness EUV light sources are of great potential interest for this industry. The recent availability of highly reflective mirrors at 13.5 nm wavelength makes EUV lithography a strong candidate for future generation semiconductor manufacture. The design is based on a storage ring lattice employing design principles similar to those used in the new family of diffraction limited synchrotron radiation sources. The 430 MeV storage ring of circumference 25.8 m would have an emittance of ~ 6 nm-rad. The required EUV wavelength is obtained using a short period (16 mm) undulator.

Presenting Author

S68

Soft X-Ray ARPES at Swiss Light Source: Electronic Structure of Device Materials

Vladimir N. Strocov

Swiss Light Source, Paul Scherrer Institute, Switzerland

Soft-X-ray ARPES in the photon-energy range around 1 keV benefits from enhanced photoelectron escape depth and resonant photoexcitation delivering chemical-state specificity. High energy resolving power (>30K) and photon flux (>10^{13} ph/s/0.01%BW) at the ADRESS beamline expand this novel experimental technique to previously unthinkable buried heterostructures and impurities, which are in the heart of electronic and spintronic devices.

Semiconductors are illustrated by AlGaN/GaN heterostructures, where soft-X-ray ARPES finds anisotropy of the interfacial quantum-well states, resulting in anisotropic high-field electron transport [Lev et al., *Nature Comm*. **9** (2018) 2653]. For the oxide interfaces $LaAlO_3/SrTiO_3$, resonant photoexcitation of the Ti-derived interfacial charge carriers resolves their multiphonon polaronic nature, fundamentally limiting their mobility [Cancellieri et al., *Nature Comm*. **7** (2016) 10386]. Further cases include EuO/Si spin injectors, EuS/Bi_3Se_2 topological interfaces, etc.

Impurity systems are illustrated by Ga(Mn)As, where resonant photoexcitation of Mn-derived impurity states identifies their energy alignment and hybridization with the GaAs host [Kobayashi et al., Phys. Rev. B **89** (2014) 205204]. Other cases include magnetic V impurities in the topological Bi_3Se_2 competing with the quantum anomalous-Hall effect, etc.

Presenting Author

S69

Soft x-ray Photoelectron Spectroscopy for Device Physics at the PEARL Beamline

Matthias Muntwieler

PSI

The demand for smaller device structures poses several challenges on the development of future microtechnology since the control of the quality of deposited structures, such as shape definition, chemical purity, absence of structural defects becomes more important.
In general, the larger surface-to-volume ratio of small structures enhances surface and interface effects over bulk properties, which suggests that surface science techniques may help to understand and resolve some of the issues.

The PEARL (photoemission and atomic resolution laboratory) beamline at the SLS has been designed for a broad range of surface studies. Its scientific program covers a wide range from fundamental to applied surface science on the micro- to nano-scale with a focus on novel functional materials and device concepts. At its core, it features a continuously tunable photon source from 70 to 2000 eV for angle-resolved photoelectron spectroscopy (XPS/ARPES), which is complemented by a surface preparation facility and a scanning tunneling microscope.

In the context of EUV lithography, for example, novel photoresist materials and concepts have been studied. Thanks to the wide photon energy range, a photoresist sample can be exposed to EUV radiation and analyzed using photoelectron spectroscopy in-situ and on the same spot. This procedure allows to study changes of chemical environment in the photoresist upon exposure and clarify the chemical reaction that occur. Though the current spot size (at 70 um) is hardly comparable to current technological length scales, planned developments of the x-ray optics will reduce the size gap between scientific samples and technology.

Presenting Author

S70

XRnanotech – A PSI Spin-Off for EUV and X-ray Optics

Florian Döring

Paul Scherrer Institut, 5232 Villigen-PSI, Switzerland

EUV and X-ray techniques like imaging, spectroscopy or scattering allow investigating matter with spatial, temporal and spectroscopic resolution. In order to achieve best possible results in these fields, cutting-edge optics are needed.

At the Paul Scherrer Institut (PSI) in Switzerland, we developed nanostructured diffractive EUV and X-ray optics with very high structural quality. Now, we are making these commercially available with the PSI spin-off XRnanotech. The fundamental advantage of diffractive optics compared to other kinds of X-ray optics (e.g. mirrors and lenses) is their possibility to precisely control the optical wave front that allows realising unique optical functionalities. In this contribution, we present a variety of optical elements shown in Figure 1, which were used for EUV and X-ray applications.

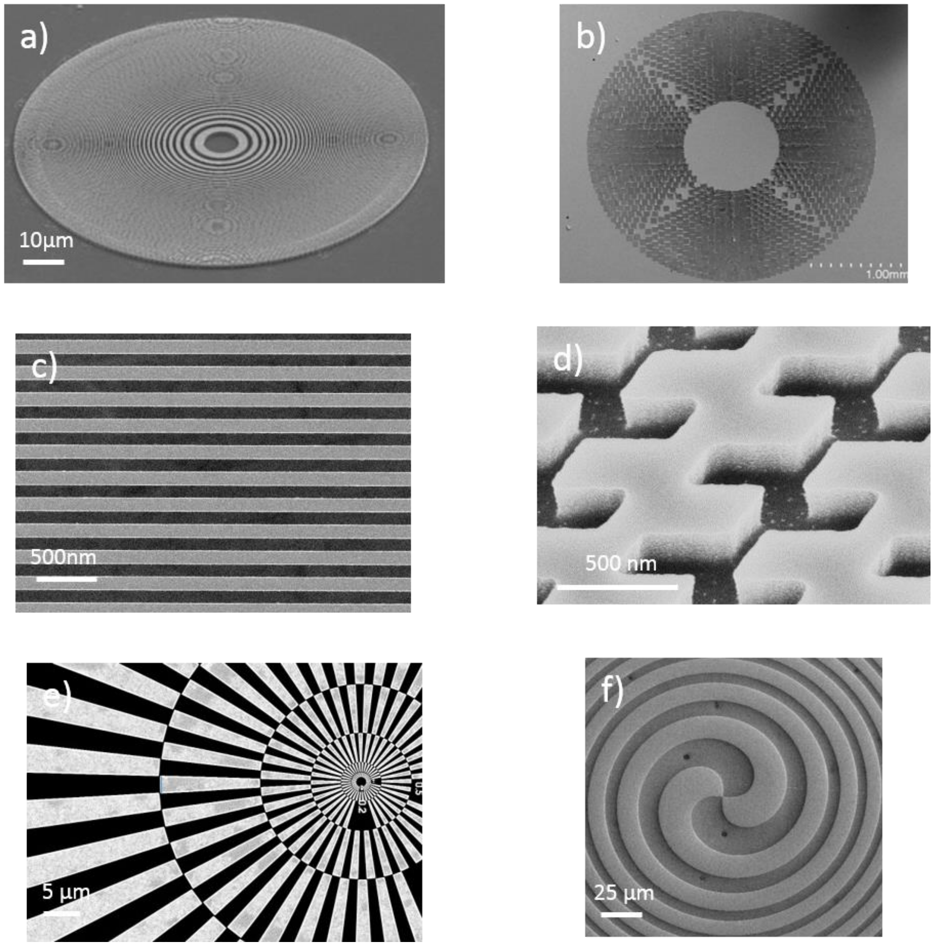

Fig.1: Examples of nanostructured diffractive X-ray optics available from XRnanotech. a) Fresnel zone plate, b) beam shaping condenser, c) transmission diffraction grating, d) customized multifunctional optics, e) X-ray test standard, f) spiral zone plate

Presenting Author

S71

AAT: The Venture of Accelerating PSI's Accelerator Technologies for the Industry

Jens Rehanek

Advanced Accelerator Technologies AG

Advanced Accelerator Technologies AG (AAT) has been founded on an initiative of the Paul Scherrer Institute (PSI) in 2015 in order to intensify the commercialization of its experience and knowhow in accelerators and large scientific infrastructure development and operation as well as the broad spectrum of their applications. As part of the national initiative Switzerland Innovation, AAT is in PARK INNOVAARE at PSI in Villigen, Switzerland. AAT is set up as a joint venture of industry leaders in the large science and high-tech enterprises supply markets, injecting their specific industrial skills, experience and strengths in order to create higher customer value by combining with PSI‘s vast R&D expertise.

Presenting Author

S72

Displacement Talbot Lithography: A New Technology for Printing Periodic Nanostructures over Large Areas

Harun H. Solak

Eulitha AG, 5416 Kirchdorf, Switzerland

High-resolution periodic patterns such as gratings or two-dimensional arrays are required in many applications, especially in photonics devices such as near eye displays or DFB lasers. In order to address this growing need, we introduced a photolithography technique called Displacement Talbot Lithography (DTL) that enables low-cost patterning of large areas. DTL offers resolution below 100nm which is sufficient even for demanding applications that require sub-wavelength resolution such as wire-grid polarizers. Eulitha provides tools for research and industrial use of DTL in various fields.

Presenting Author

S92

Radiation Hydrodynamic Simulation Code STAR2D (Invited)

Atsushi Sunahara[1], Katsunobu Nishihara[2] and Akira Sasaki[3]

[1] *Center for materials under extreme environment (CMUXE),Purdue University, USA*
[2] *Institute of Laser Engineering, Osaka University. JAPAN*
[3] *Kansai Photon Science Institute, National Institute for Quantum and Radiological Science and Technology, JAPAN*

Star2D is the 2-d radiation hydrodynamic simulation code, which has been developed at Osaka University since 2003, for simulating the dynamics of the laser-produced plasmas, such as the extreme ultraviolet (EUV) emission or inertial confinement fusion. This code treats one fluid two-temperature model, and solves the conservative Euler system equations based on HLLC scheme [1, 2] for conserved variables such as density, momentum, and total energy density (ρ, ρu, ρet) with 2nd order slope limiter [3] in space and 2nd order time integration [4]. Also it solves the non-conservative equations of ion and electron temperatures (T_i, T_e). The realistic equation of state (EOS) is incorporated. The radiation spectrum is solved by the flux-limited diffusion model, using emissivity and opacity data calculated based on the collisional radiative steady state (CRSS) and the local thermal equilibrium (LTE) atomic models [5]. We have applied STAR2D code to the EUV plasmas, showed that the emitted radiation spectrum and the conversion efficiency (CE) of 3-6 % bandwidth at 13.5nm with 10.6 μm wavelength laser irradiation on tin droplet plasmas [6]. We will show simulation results for Test Problem – 1d laser absorption and Bonus Problem – time dependent laser absorption. The results of the 1D calculation were obtained by removing many physical models from the original 2D program and changing to a simplified model such as LTE and one temperature model.

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Presenting Author

Katsunobu Nishihara is Professor Emeritus, Osaka University and he is also Visiting Professor in Graduate School of Engineering, Osaka City University and Institute of Laser Engineering, Osaka University. He received his doctor of engineering in 1973 from Osaka University. Prior working at Institute of Laser Engineering at Osaka University 1976, he worked at Bell Laboratory in USA and Faculty of Science at Nagoya University. His research interests include plasma physics, laser fusion research, nonlinear science and computational science. He was working mainly on theory and computer simulations in these scientific fields. He played a leading role in a project of LPP EUV source development in Japan since 2003, especially in modeling the source plasmas.

S93

JATOM Code for Calculation of Atomic Processes in Sn Plasmas (Invited)

Akira Sasaki[1], Katsunobu Nishihara[2], and Sunahara Atsushi[2,3]

[1]Kansai Photon Science Institute, National Institutes for Quantum and Radiological Science and Technology, 8-1 Umemidai, Kizugawa-shi, Kyoto, 619-0215 Japan,
[2]Institute for Laser Engineering, Osaka University
[3]CMUXE, Purdue University

JATOM code was developed to provide the emissivity and opacity of Sn plasmas as well as the mean charge and internal energy of ions, which are parts of the equation of state (EOS) data [1]. The code was based on the collisional radiative model including Sn ions, which contribute to the emission and absorption in the 13.5 nm band. The code used DCA (Detailed Configuration Accounting) approach to determine the atomic model, which consists of a set of atomic states, which were defined by their electron configuration (*nl*)1, (*nl*)2, … . The energy levels, rate of radiative decay and auto-ionization were calculated by the HULLAC code [2] with the configuration average mode. Inner shell and multiply excited states were included to take the emission from these state into account [3,4]. Rates of other processes of atomic ionization and excitation were calculated using empirical formulas. Calculation of radiative properties of the plasmas was carried out using a multi-step approach. For transitions between atomic states in the 13.5 nm band, the profile of the UTA (Unresolved Transition Array) was calculated using HULLAC code taking CI (Configuration Interaction) into account.

Furthermore, the wavelength of each UTA was corrected by the observation using CXS (Charge eXchange Spectroscopy) [5]. The calculation was validated after a series of convergence analysis changing the atomic model. Tabulated emissivity and opacity within the range of ion density and electron temperature of 1015-23 /cm3 and 10 – 50 eV, respectively was calculated and brought into the hydrodynamics simulation [6]. For the emission and absorption, typically, 1,500 meshes were placed between 0 to 1,500 eV, with the finest meshes of ΔE = 0.2 eV were placed in the photon energy range between 50 to 200 eV.

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Presenting Author

Akira Sasaki obtained Dr. Eng. from Tokyo Institute of Technology in 1981, and joined Japan Atomic Energy Research Institute in 1996, the organization of the institution has changed since to present National Institute for Quantum and Radiological Science and Technology. He is interested in the modeling of atomic process and spectroscopy of the plasmas based on the computational atomic data. He is also interested in the complexity of the materials and its modeling using statistical methods. He has been involved in the research project for the EUV lithography especially for the source modeling since 2003.

S95

Modeling Laser Energy Deposition with the RALEF Code (Invited)

Mikhail M. Basko

Keldysh Institute of Applied Mathematics (KIAM), Moscow, Russia

This presentation for the code comparison session is limited to the proposed test problem on laser absorption in 1D geometry, simulated with the 2D radiation hydrodynamics code RALEF that has been extensively used in recent years at KIAM and ARCNL to study laser targets for 13.5-nm EUV light sources. The three basic options for modeling laser transport, implemented in the RALEF code, are briefly described together with the underlying physical and mathematical models. The test-problem results for the three different transport modes are discussed and compared between themselves.

Presenting Author

Mikhail M. Basko holds the position of a leading researcher at the Keldysh Institute of Applied Mathematics (KIAM) in Moscow since 2012. His research activity at KIAM has been to a large degree focused on numerical modeling of laser driven targets for 13.5-nm EUV light sources. Before that, having been employed for more than 30 years at the Institute for Theoretical and Experimental Physics (Moscow), he was heavily involved in an ambitious project of developing the theoretical basis for inertial confinement fusion driven by intense beams of heavy ions. During this period, he spent much time on multiple 3- to 12-months visits as a guest researcher at the Max-Planck Institute for Quantum Optics in Garching (Germany), at the GSI accelerator center in Darmstadt (Germany), at the CEA center in Cadarache (France), as a guest professor at the Institute for Laser Engineering in Osaka (Japan), and as a Visiting Fellow at JILA in Boulder (Colorado, USA). His publication list includes more than 120 scientific papers.

He obtained his MS degree from the Moscow Institute of Physics and Technology in 1971, and a PhD degree in the field of high energy astrophysics from the Institute for Space Research (Moscow) in 1974.

S96

THERMOS Toolkit: Software Package for Radiative Properties Calculations of LTE and Non-LTE Plasmas (Invited)

Vichev I.Yu., Solomyannaya A.D., Grushin A.S., Kim D.A.

Keldysh Institute of Applied Mathematics, Miusskaya sq., 4, Moscow, Russia

THERMOS Toolkit [1] has been developed at the Keldysh Institute of Applied Mathematics, it consists of set of atomic databases and software package, which is designed for calculation of thermodynamic and radiative properties of plasma at various conditions over wide range of temperatures and densities.

The software package includes codes for numerical simulation of transparent and optically thick plasmas. The local thermodynamical equilibrium (LTE) plasma properties are calculated by using the self-consistent Hartree-Fock-Slater model or Saha-Boltzmann statistics with atomic database. For Non-LTE cases the system of level kinetics equations is solved in the quasi-stationary approach with a fixed radiation field by using the collisional-radiative equilibrium (CRE) model with atomic databases.

The specifics of the EUV plasma source simulation is that it requires high accuracy of spectral line positions in order to successfully predict emission of plasma within the narrow 2% bandwidth window centered at 13.5 nm. Therefore in the atomic database, that had been initially calculated with non-relativistic isolated average ion model, configuration energies and spectral lines positions were refined with aid of detailed atomic codes [2, 3] and available experimental data. The resulting RDCA (Reduced Detailed Configuration Accounting) database allows one to obtain realistic emission spectra of plasma within the aforementioned wavelength interval.

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Calculations have been performed at HPC MVS-10P (JSCC RAS) and HPC K100 (KIAM RAS).

Presenting Author

Ilya Vichev is currently a junior scientist researcher at the Keldysh Institute of Applied Mathematics of the Russian Academy of Science. He completed his MSc in applied mathematics and physics at the Moscow Engineering Physics Institute (State University) in 2007, with a focus on modeling of the emission spectra of multicharged ions in non-LTE plasma. In 2013-2017 as a member of the KIAM-ISAN-ASML collaboration, he worked on the modeling of a droplet morphology after the laser pre-pulse which was of interest in the development of EUV sources. He is currently completing work on his PhD in modeling of plasma radiative properties under the LTE and non-LTE conditions.

S97

Radiation Physics Models for High Energy Density Plasmas, Typical Applications for EUV Lithography (Invited)

I.E. Golovkin

Prism Computational Sciences, Inc. Madison, WI

Prism Computational Sciences, Inc. has developed a variety of modeling tools to study radiative properties of high energy density plasmas (HEDP). Radiative and atomic processes in plasmas play a critical role in a wide variety of HEDP systems. The emission, absorption, and transport of radiation can strongly affect the overall energetics and evolution of such plasmas. In addition, radiation-based diagnostics – including imaging, spectroscopy, and absolute flux measurements – are widely used to determine key properties of HEDPs. We will briefly discuss simulation models developed at Prism and their applications related to EUVL. Prism software features sophisticated numerical models for performing simulations, in combination with easy-to-use graphical interfaces and interactive visualization tools. These software tools are well-suited for government and industrial laboratory research, as well as undergraduate and graduate student research and education projects.

Presenting Author

Dr. Igor Golovkin is a CTO at Prism Computational Sciences, Inc. He has decades of experience in research related to radiative properties of HEDP. His efforts focus on developing models that include non-equilibrium collisional-radiative atomic kinetics, line broadening, and opacity effects to perform spectroscopic and hydrodynamics simulations for different applications, especially implosion experiments relevant to inertial confinement fusion, laboratory astrophysics, industrial plasmas, and plasmas driven by short pulse lasers.

S98

Atomic Kinetics Modelling of Sn Plasmas using ATOMIC (Invited)

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

[1]Advanced Research Center for Nanolithography, Science Park 106, 1098 XG Amsterdam, The Netherlands
[4]Los Alamos National Laboratory, Los Alamos, NM 87545, USA

We have employed the Los Alamos suite of atomic and population kinetics codes [1] to address the 0D atomic kinetics problem in the code comparison session of the 2020 EUV Source workshop. Atomic structures (wavefunctions, energy levels, oscillator strengths) have been generated using the CATS code [2], an adaptation of Cowan's original atomic structure code [3]. The configuration sets employed in the atomic models for Sn^{10+} - Sn^{14+} include large numbers of singly-, doubly-, trebly- and quadruply-excited configurations and are based on our recent work [4]. Charge-state distributions, average charge state <Z> and level-resolved bound-bound opacities and emissivities have been computed at the relevant plasma conditions using the ATOMIC code [5, 6] in its local-thermodynamic equilibrium mode.

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Presenting Author

John Sheil is currently a postdoctoral researcher in the EUV plasma processes group of Dr. Oscar Versolato, Professor Ronnie Hoekstra and Professor Wim Ubachs at the Advanced Research Center for Nanolithography in Amsterdam, the Netherlands. He completed both the BSc and PhD degrees at University College Dublin, Ireland. The focus of his PhD was on the spectroscopy of highly charged lanthanide ions and the identification of many-body quantum chaos in the level structures of moderately charged actinide ions. His current research interests center on various aspects of laser-produced plasma modeling, such as radiation-hydrodynamic simulations, opacity and atomic structure studies as well as modeling ion kinetic energy distributions from laser-produced tin plasmas.