2016 International Workshop on EUV and Soft X-Ray Sources (2016 Source Workshop)

November 7-9, 2016

Amsterdam ▪ The Netherlands

Workshop Abstracts

EUV Litho, Inc.

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2016 International Workshop on EUV and Soft X-ray Sources
(2016 Source Workshop)

Workshop Co-Organizers

Welcome

Dear Colleagues;

I will like to invite you to join me and our colleagues at the 2016 International Workshop on EUV and Soft X-Ray Sources (2016 Source Workshop) in Amsterdam, The Netherlands from November 7-9, 2016.

The workshop, in its 7th year, is being organized by EUV Litho Inc. in the Netherlands in collaboration with ARCNL. This change of location is allowing us to interact with many new researchers in this geographical area, who are actively working on EUV and XUV sources and applications. As in the previous years, the workshop's agenda will provide a forum for researchers in the EUV/XUV source area to present their work and discuss potential applications of their technology. I expect that researchers as well as the end-users of these sources will find this workshop valuable. As always, the workshop proceedings will be published online at our website.

This workshop has been made possible by the support of workshop sponsors, technical working group (TWG) members, workshop support staff at ARCNL, session chairs and presenters and attendees. I would like to specially thank Oscar Versolato, Joost Frenken, Marjan Fretz and Romy Metz from ARCNL, for their contributions in making this workshop a success.

I look forward to your participation and a successful workshop.

Best Regards

Vivek Bakshi
Organizing Chair, 2016 International Workshop on EUV and Soft X-Ray Sources
(2016 Source Workshop)

Source Technical Working Group (TWG)

Reza Abhari (ETH Zurich)
Peter Anastasi (Silson)
Sasa Bajt (DESY)
Vadim Banine (ASML)
Klaus Bergmann (ILT-Fraunhofer)
Davide Bleiner (University of Bern)
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Padraig Dunne (UCD)
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Akira Endo (HiLase)
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Mikhail Yurkov (DESY)
Takayuki Uchiyama (Toshiba)
Obert Wood (GlobalFoundries)
Sergey Zakharov (Naextstream)
Wim van der Zande (ASML)
Vivek Bakshi (EUV Litho, Inc.) - Organizing Chair
Oscar Versolato (ARCNL) – Co-Chair

ABSTRACTS

S1

EUVL Exposure Tools for HVM: It's Under (and About) Control (Keynote Presentation)

Wim J. van der Zande

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

EUV Lithography has made significant and impressive progress over the last few years. In the development EUV sources produce more than 200 Watt at intermediate focus. In my talk, I will discuss the position of EUV lithography in the industry, I will illustrate that not only the source itself posed a challenge, but also aspects of the tool and I will present some details on the technology behind the laser produced plasma sources.

Presenting Author

Wim van der Zande is Director of Research at ASML since 2014. Prior to 2014, he worked at the Radboud University Nijmegen and the FOM Institute AMOLF in Amsterdam concentrating on laser physics and on the interaction of light with matter from first principles to applications.

S2

X-ray Microscopy with Laboratory Sources (Keynote Presentation)

Hans M Hertz

Biomedical and X-Ray Physics, Dept. of Applied Physics, KTH/Albanova, Stockholm, Sweden

We developed the first laboratory microscope for high-resolution imaging in the water-window (approx. 0.5 keV). In its present version the microscope relies on a liquid-nitrogen-jet-target laser-plasma x-ray source, multilayer condenser optics, zone-plate imaging optics and cryogenic sample handling. The last few years the microscopes have demonstrated 3D nanotomography of cryo-fixed biological samples. The synchrotron-like image quality relies on our high-resolution and high-efficiency diffractive optics and exposure times are approaching that of bending-magnet microscopes with an upgraded laser-plasma source based on a 2 kHz diode-pumped slab laser. Recent works include improved modelling and reconstruction for higher-resolution 3D imaging at soft x-ray microscopes, where depth of focus is typically smaller than the sample size, a method to improve the source stability, and the addition of higher-reflectivity condenser mirrors. With these improvements we hope to be able to perform routine tomographic imaging of biological samples.

In an extension of the laboratory x-ray microscopy to higher energies we presently exploit the higher penetration at approx. 10 kV energies for high-spatial resolution imaging of thicker samples. Here we use the spatial coherence of our new electron-impact liquid-metal-jet-anode micro focus x-ray tube, an invention that is now being commercialized. Applications include phase-contrast imaging of, e.g., the 3D microvasculature in mouse organs and ears and the soft-tissue structure of intact zebrafish with subcellular resolution.

Presenting Author

Hertz received his Ph.D. in optical physics 1988 at Lund University, Sweden and did his post-doc at Dept. of Applied Physics, Stanford University. Since 1997 he is a professor in Biomedical Physics at the Royal Inst. of Technol. (KTH), Stockholm. Here he leads a □30-person cross-disciplinary research group with focus on x-ray science and technology including optics, nanoparticles, ultrasonics, and bioengineering.

He pioneered the liquid-jet laser-plasma source, the liquid-metal-jet electron-impact source and laboratory x-ray microscopy, and the research has resulted in a few spin-off companies. His present research interests include x-ray sources and x-ray optics, high-resolution phase-contrast x-ray imaging, x-ray fluorescence imaging, and x-ray microscopy. From 2006 to 2012 he was the first head of the Dept. of Applied Physics. In spring 2013 he was a visiting professor at Dept. of Radiology, Stanford University and in fall 2014 he was a fellow at Stellenbosch Inst. of Advanced Studies, South Africa. He is presently chairman of the Board of the MAX IV Laboratory (Lund) and Excillum AB (Stockholm). He is a fellow of the Royal Academy of Sciences (KVA) and the Royal Swedish Academy of Engineering Sciences (IVA). He has published >140 scientific papers, holds >25 patents, and has advised >25 PhDs.

S3

Interferometry, Spectroscopy and Lensless Imaging with Extreme-ultraviolet Radiation (Keynote Presentation)

Stefan Witte

ARCNL and VU University Amsterdam

Lasers have given researchers the ability to produce bright coherent beams of light. Having a coherent light source enables a wealth of experiments that provide access to the phase of the light waves rather than just the intensity. High-harmonic generation (HHG) is a process that enables the production of fully coherent pulses of extreme-ultraviolet (EUV) and soft-X-ray radiation using compact high-intensity lasers. The short-wavelengths and associated high photon energies of EUV radiation give rise to very different light-matter interaction compared to visible light: EUV radiation can penetrate optically opaque materials, but can also be used to probe inner-shell electrons in atoms and molecules.
The ability to perform interferometry with HHG sources would enable the translation of powerful optical methods such as Fourier transform spectroscopy and coherent imaging to the EUV spectral range. However, due to the short wavelengths involved, the extreme stability requirements and optical components pose a challenge. I will explain our approach to ultra-stable interferometry with HHG sources, and discuss various experiments that we have performed using coherent EUV radiation.

Presenting Author

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

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

S11

Development of 250 W LPP EUV Light Source for HVM Lithography

T. Yanagida, S. Nagai, G. Soumagne, K. M Nowak, Y. Kawasuji, H. Tanaka, H. Hayashi, Y. Watanabe, T. Hori, Y. Shiraishi, T. Yamada, T. Abe, T. Okamoto, T. Kodama, H. Nakarai, T. Yamazaki, T. Saitou and H. Mizoguchi

Gigaphoton Inc., 3-25-1 Shinomiya, Hiratsuka-shi, Kanagawa 254-8555, Japan

Gigaphoton Inc. is developing a laser produced plasma (LPP) EUV light source for high volume manufacturing (HVM) semiconductor lithography. LPP with a tin droplet target and a CO_2 pulsed laser is the most promising method for high power 13.5 nm EUV light generation. Several implemented technical key features such as a solid-state short-pulsed pre-pulse scheme and tin plasma mitigation with a magnetic field enable high power and stable operation.

So far, an average clean power of 130 W for 119 hours has been demonstrated in our prototype EUV light source. Also, maximum average clean power of 250 W with conversion efficiency (CE) of over 4% has been recorded in short term operation.

A 250 W pilot light source will soon start operation. For this source, the power of the CO_2 laser will be upgraded from the current 20kW (prototype source) to 27 kW at a repetition rate of 100kHz. The latest performance of the both light sources (prototype and pilot) will be reported.

Presenting Author

S12

Correlation of Fundamental Plasma Parameters with EUV Emission Profiles of Laser-produced Sn Plasmas for EUV Lithography Light Sources

Kentaro Tomita[1], Yuta Sato[1], Syoichi Tsukiyama[1], Toshiaki Eguchi[1], Kiichiro Uchino[1], Kouichiro Kouge[2], Tatsuya Yanagida[2], Hiroaki Tomuro[2], Yasunori Wada[2], Masahito Kunishima[2], Takeshi Kodama[2], Hakaru Mizoguchi[2]

[1] Interdisciplinary Graduate School of Engineering and Sciences, Kyushu University, 6-1, Kasugakoen, Kasuga, Fukuoka 816-8580, JAPAN
[2] Gigaphoton Inc., 400 Yokokurashinden Oyama, Tochigi, 323-8558, JAPAN

We acquire spatial profiles of fundamental plasma parameters, such as electron density (n_e), electron temperature (T_e), and averaged ionic charge (Z) of laser-produced Sn plasmas for EUV lithography, whose conversion efficiencies are 2.8-4.0%, using the ion feature of collective Thomson scattering[1, 2]. The Sn plasmas were produced with three different conditions. For all plasma conditions, intense EUV was only observed for sufficiently high T_e with Z > 10. Parameter n_e ranges as 10^{24}-(2×10^{25}) m^{-3}. These plasma parameters lie in a range of efficient EUV-light-sources, as predicted by simulations. Our results also indicate that conditions of Sn atomic density before producing plasmas affects these plasma parameters, particularly n_e.

References
1) Kentaro Tomita et al.:" A Collective Laser Thomson Scattering System for Diagnostics of Laser-Produced Plasmas for Extreme Ultraviolet Light Sources", Appl. Phys. Express 6, 076101 (2013).
2) Kentaro Tomita et al.:" Development of a collective Thomson scattering system for laser-produced tin plasmas for extreme-ultraviolet light sources", Appl. Phys. Express 8, 126101 (2015).

Presenting Author

Dr. Kentaro Tomita is a 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 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.

S13

Power Scaling of Pico-second Thin Disc Laser for LPP and FEL EUV Sources

Akira Endo

HiLASE Centre, Dolni Brezany, Czech Republic

Recent progress of thin disc lasers is promising to realize high average power EUV sources by laser plasma or FEL. Target initialization is critical for higher CE and full ionization of tin droplet in LPP EUV source, and it is well known of the advantage of pico second solid state laser. Seeding of FEL is critical to reduce pulse spikes and stabilization of FEL amplification, which is supported by high average power pico second solid state laser. Regenerative amplification in thin disc laser is possible to supply >mJ pulse energy at > 100kHz with excellent beam quality. Further progress is possible by an advanced cryogenic technology with its higher thermal conductivity. It is reported in the talk as these laser progresses are contributing in the actual EUV sources.

Presenting Author

S14

Dynamics of a Metallic Micro-droplet upon Interaction with Nanosecond Laser Pulse

D. Kurilovich[1,2], A. Klein[3], F. Torretti[1,2], M. Noordam[1], J. Scheers[1,2], W. Ubachs[1,2], R.A. Hoekstra[1,4], H. Gelderblom[3], O.O. Versolato[1]

[1]*Advanced Research Center for Nanolithography (ARCNL), Science Park 110, 1098 XG Amsterdam, The Netherlands*
[2]*Department of Physics and Astronomy, and LaserLaB, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*
[3]*Physics of Fluids Group, Faculty of Science and Technology, MESA+Institute, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*
[4]*Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*

We present our findings on the dynamics of a liquid metallic microdroplet interacting with a Nd: YAG nanosecond-pulse laser. By implementing shadowgraphy imaging techniques, the droplet's response to laser-pulse impact is investigated [1]. The experimental results obtained with this tool unveil a scaling law that describes the plasma-imparted momentum transfer over nearly three decades of laser energy. Moreover, the subsequent deformation of the droplet finds its description in a fluid-dynamic analytical model. The comparison of our results with those from the experiment with millimetre-sized water droplets demonstrates scalable behaviour of the fluid-dynamic response and its decoupling from the propulsion mechanism.

[1] D. Kurilovich *et al.*, Phys. Rev. Applied **6**, 014018 (2016)

Presenting Author

Dmitry Kurilovich is a Ph.D. student in the Advanced Research Center for Nanolithography (ARCNL) in Amsterdam, The Netherlands. His current research activities are focused on laser-droplet interactions and plasma diagnostics in an EUV light source based on a laser-produced tin plasma.

S15

High-radiance LDP Source: Clean, Reliable and Stable EUV Source for Mask Inspection

Yusuke Teramoto, Bárbara Santos, Guido Mertens, Ralf Kops, Margarete Kops, Hironobu Yabuta, Akihisa Nagano, Noritaka Ashizawa, Yuta Taniguchi, Daiki Yamatani, Takahiro Shirai, Kunihiko Kasama, Alexander von Wezyk[1] and Klaus Bergmann[1]

Ushio Inc.
[1]Fraunhofer ILT

High-throughput actinic mask inspection tools are desired as EUVL begins to enter into volume production phase. One of the key technologies to realize such inspection tools is a high-radiance EUV source of which radiance is as high as 100 W/mm2/sr. Ushio is developing laser-assisted discharge-produced plasma (LDP) sources. Ushio's LDP source is able to provide sufficient radiance as well as cleanliness, stability and reliability. Radiance behind the debris mitigation system was confirmed to be 120 W/mm^2/sr at 9 kHz and peak radiance at the plasma can be as high as 180 W/mm^2/sr. One of the unique features of Ushio's LDP source is cleanliness despite liquid tin used as fuel material. Source cleanliness was evaluated through many sample exposures behind the debris shield. Deposition of tin was negligible and sputter rate was a few nm per Gpulse. We recently introduced a high opening-angle version, in which the opening angle is 28°, to allow for the future demands. Days-long, non-interrupted runs were also carried out to address system reliability and long-term stability.

Presenting Author

He received Ph.D. degree in 2002 from Kumamoto University, Japan. He joined Ushio Inc. in April 2002 and started research and development on Xe and Sn fueled discharge EUV source. 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, especially in power scaling. Now he is a senior project manager and in charge of Germany unit to conduct marketing and development of EUV source for mask inspection and non-litho applications.

S16

Droplet-based High Brightness LPP Light Sources for High Volume Metrology and Inspection Applications

Reza S. Abhari, Markus Brandstaetter, Duane Hudgins, Alexander Sanders, Marco Weber, Daniel Boehringer[1]

Laboratory for Energy Conversion, Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland

[1]Adlyte AG, Zug, Switzerland

EUV mask infrastructure including actinic blank and mask inspection is of key importance for the introduction of EUV lithography into high volume manufacturing. At ETH Zurich, a tin droplet-based laser-produced plasma source with application in EUV lithography is under continuous operation since Q3 2013. The EUV source ALPS II is equipped with a large capacity droplet dispenser and a high power (kW), high repetition rate (>6 kHz) Nd: YAG laser. This source addresses the requirements of high volume manufacturing for inspection and metrology applications found in EUV lithography. The average source brightness is equal to 350 W/mm2sr. Debris mitigation is a critical factor effecting the lifetime and cost of ownership of metrology EUV sources. The major challenge of debris generation in metrology EUV sources is associated with high kinetic energy ions and neutral debris clusters from the ablated droplets.

In the first part of this work an improved droplet generation excitation system is proposed facilitating the uniform generation of micrometer-sized molten tin droplets. In the second part of this work the droplet breakup from nanosecond laser pulses was investigated. The coupling between laser-droplet misalignment and the debris distribution was measured experimentally using a high speed shadowgraph imaging system. A model of the relationship between the droplet-laser misalignment and the debris trajectory is proposed for describing the experimental results. In the final part of this work an enhanced debris mitigation system employing a three-layer strategy introducing a localized high-momentum flow is presented demonstrating the cleanliness of the EUV source for a GI collector configuration. Results from testing for long term source operation are presented including results from sample tests from the first collector optics. In summary, the impact on the lifetime of the source is discussed.

Presenting Author

S17

Scaling of Discharge based XUV Sources for Metrology Applications

Klaus Bergmann, Alexander von Wezyk, Jochen Vieker

Fraunhofer Institute for Laser Technology – ILT,
Steinbachstr. 15, 52074 Aachen, Germany

Basic considerations on power and brightness scaling of compact discharge based sources will be presented. The experimental platforms are the latest source generations for soft x-ray and extreme ultraviolet radiation, which are under development at Fraunhofer ILT. The xenon based FS5440 is capable of a continuous 2% in-band emission at 13.5 nm of more than 40 W/2□sr and an in-band peak brightness of more than 12 W/mm^2/sr. The nitrogen based FS0740 source is delivering a peak brightness of $4.0*10^9$ Ph/s/µm^2/sr at the 2.88 nm helium-like resonance line. The scaling potential will be discussed based on new results of basic experiments which allow for an access to a larger parameter range with respect to pressure, electrode design and electrical circuit parameter.

Presenting Author

Klaus Bergmann received the M.S. degree in physics and Ph.D. degree from the University of Technology, Aachen, Germany, in 1992 and 1996, respectively. Since 1992, he has been with the Department for Plasma Technology, Fraunhofer Institute for Laser Technology. He was occupied with the investigation of plasma focus devices as radiation sources in the soft X-ray range and pseudospark switches for applications for high pulsed currents. Currently, he is Group Leader for the development of radiation sources for use in future semiconductor lithography. The focus of work is the scaling of gas discharge based EUV-sources and their application in structuring and analysis.

S18

A High-Brightness LPP EUV Source based on Liquid Lithium Jet for Actinic Mask Inspection

Konstantin Koshelev, Alexander Vinokhodov, Mikhail Krivokoritov, Oleg Yakushev, Denis Glushkov, Pavel Seroglazov, Samir Ellwi

RnD-Isan, Moscow, Russia
ISTEQ B.V., Eindhoven, the Netherlands

ISTEQ/RnD-ISAN has for many years been focused on developing a unique target approach for a laser-produced plasma EUV source to fulfill actinic mask inspection requirements. The main critical parameters of this source are high brightness, dose stability, long lifetime (minimum amount of debris) and compact size. In addition to the conventional droplet target scheme which we use with a low melting temperature tin alloy as a fuel we have developed a new "no debris" concept based on a liquid lithium jet. This target is placed inside a compact closed volume (vacuum chamber) with self-cleaning input and output windows. This concept provides a number of significant advantages, providing higher EUV dose stability and longer optics lifetime. This makes the use of lithium as a fuel for EUV sources highly attractive. New experimental data will be presented.

Presenting Author

Dr. Samir Ellwi currently holds the position of Non-Executive Managing Director at ISTEQ B.V., a company which specializes in the development and manufacturing of light sources ranging from soft X-rays to infrared. He is the co-founder and CEO of ALSPhotonics, a consultancy company concentrating on light sources and their applications. He has more than 20 years' experience in laser, laser applications and light sources. He holds a PhD from University of Essex/UK "X-ray and Optical Studies of Dense Plasmas". Prior to ISTEQ, he worked as a Managing Director at Adlyte/Switzerland, a company specializing in the development of EUV light sources. Previously he was Vice President at Powerlase/UK and a member of the executive management team. He worked as a senior scientist in the research group at ASML.

S19

Progress Towards Actinic Patterned Mask Inspection

Oleg Khodykin

RAPID, KLA-Tencor Inc.

Significant progress has been reported by EUV scanner supplier towards delivering productivity, availability and operational expenses consistent with cost-effective HVM, the semiconductor industry needs to work on a well-known list of supporting technologies like bright, stable EUV sources for actinic mask metrology tools as well as development of mask inspection tools (blanks, aerial image, and pattern).

RAPID division of KLA-Tencor has been providing patterned mask inspection tools for semiconductor industry for more than 30 years and has been working on EUV actinic patterned mask inspection solution since late 2008. In this presentation, we are going to present overview of latest progress in developing critical subsystems, primary bright and stable EUV source.

Presenting Author

Oleg Khodykin is a Manager of EUV source development in KLA-Tencor's RAPID division in Milpitas, California. Prior joining KLA-Tencor in 2011, he worked at CYMER (now ASML company) for 10 years as a senior scientist and EUV collector group leader on different concepts of EUV source (both discharge and LPP, lithium, xenon and Sn based). Dr. Khodykin received his Ph.D. from Moscow Physical-Technical Institute in 1998 and did postdoctoral training at Bayreuth University and at the University of Southern California.

S21

Conversion Efficiency of Laser-produced Plasmas at 13.5 nm and Colliding Plasmas as EUV Sources

Gerry O'Sullivan, Thomas Cummins, Tony Donnelly, Padraig Dunne, Paddy Hayden, Domagoj Kos, Oisín Maguire, Fergal O'Reilly and Emma Sokell

School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

Although the maximum predicted conversion efficiency (CE) of laser produced plasma Sn based sources is around 8%, sources for high volume manufacturing typically report CE values of 4% and in exceptional circumstances have recorded CEs approaching 5.5%. The maximum reported CE from a Sn droplet source is 6.5% recorded at the Institute of Laser Engineering in Osaka University using Nd: YAG pre-pulse, CO_2 main pulse illumination. To explore if the predicted value could be obtained, a colliding plasma experiment using a Sn wedge target was performed at UCD. A Nd: YAG 270 mJ pre-pulse split equally between two focal spots and focused t o a power density of $\sim 1.0\times10^{11}$ Wcm^{-2} provided the pre-pulses which generated two interpenetrating plasmas that formed a stagnation layer that in turn, acted as a target for a 250 mJ, $\Phi = \sim 1.7\times10^{9}$ Wcm^{-2}, CO_2 main pulse. A CE = 3.6±0.2% was obtained. However, when allowance was made for the long, low power density tail of the CO_2 pulse and the spatial mismatch between the target and the CO_2 beam profile, this figure increased to approximately 7%. This result suggests that under optimum conditions, a CE of close to 8% should indeed be obtainable.

Presenting Author

S22

Physics of Laser Ablation and the Quest for Maximum CE

M. M. Basko

Keldysh Institute of Applied Mathematics (KIAM), Moscow, Russia
RnD-ISAN/EUV Labs, Moscow, Troitsk, Russia

Collisional-radiative models of the Sn plasma predict a spectral purity (into the 2% bandwidth around 13.5 nm and into 4π sr) of up to 40%, which implies that static uniform Sn-plasma volumes can demonstrate a conversion efficiency (CE) into 2π sr of ≈20%. As one of the closest to static realistic configuration, we set up and solve the problem of full CE optimization by *steady-state laser ablation* of Sn droplets. It is shown that the optimization must be performed with respect to only two essential parameters, namely, the EUV source radius R_{mc} (controlled by either the droplet radius or a separate "slave" laser pulse) and the main pulse intensity I_{ml}. For the CO_2 main laser, the absolute maximum steady-state CE = 9% is reached at $R_{mc} \approx 300\mu m$ and $I_{ml} \approx 8\times10^9$ W/cm^2; the maximum transient-peak CE ≈ 12% occurs at $R_{mc} \approx 150\mu m$ and $I_{ml} \approx 10^{10}$ W/cm^2. The physical factors, stemming from the basic laws of laser ablation and bringing down the optimized realistic CE to about one half of its absolute theoretical maximum of ≈20%, are analyzed in detail.

Presenting Author

Prof. Mikhail Basko is a physicist and a leading researcher at the Keldysh Institute of Applied Mathematics (KIAM), Russian Academy of Sciences, Moscow.

S23

Cross-sections for Electron-impact Ionization of Tin ions from a Crossed-beams Experiment

Stefan Schippers

Atom und Molekülphysik, I. Physikalisches Institut, Justus-Liebig-Universität Gießen
Leihgesterner Weg 217, 35392 Gießen, Germany

Electron-impact ionization (EII) is the most important atomic process leading to the ionization of a hot plasma. Consequently, accurate cross sections for EII are required for the modelling and, thus, for a detailed understanding of the charge balance in collisionally ionized plasmas. Experimentally, such cross sections can be obtained from colliding-beams experiments. In my talk, I will introduce the electron-ion crossed-beams technique and present recently published results for EII of tin ions in charge states ranging from 4 to 13 [1]. This range includes the charge states that are most relevant for the generation of 13.5-nm EUV radiation.

[1] A. Borovik Jr., M. F. Gharaibeh, P. M. Hillenbrand, S. Schippers, and A. Müller, J. Phys. B 46 (2013) 175201.

Presenting Author

Stefan Schippers received his doctoral degree from the Department of Physics, University of Osnabrück, Germany. Subsequently, he spent three years as a postdoc at the University of Groningen, The Netherlands. Currently, he is an adjunct professor and research-group leader at the Justus-Liebig-University Giessen, Germany. In his research, he investigates the interactions of ions with photons, electrons, atoms and solid surfaces, covering topics ranging from fundamental atomic and molecular physics to applications in plasma and astrophysics.

S24

Charge-state Resolving Analysis of EUV Spectra using Electron-beam Ion Traps

José R. Crespo López-Urrutia

Max-Planck-Institut für Kernphysik, D-69117 Heidelberg, Germany

EUV plasma sources are often pulsed, thus their understanding based on a purely spectroscopic analysis is challenging due to the presence of time dependent, strong spatial gradients. From the side of atomic theory, intricate electronic structures and the existence of unresolved transition arrays complicates the assignment of spectral features even to the ionic charge states. Understanding such plasmas calls for the application of electron beam ion traps (EBITs), where rather pure charge states can be prepared for spectroscopic observation. Beyond obtaining EUV spectra at high resolution for individual charge states, by simultaneously recording optical and soft x-ray spectra and tuning the electron beam energy to investigate the strong resonant excitation mechanisms, a very complete picture of the electronic properties of the highly charged plasma ions can be gained. Furthermore, EBIT-based photon absorption studies at free-electron laser (FEL) and synchrotron facilities deliver information on key parameters related to oscillator strengths and opacities. These investigations can approach a photon-dominated regime thanks to the high power densities available at FELs, and provide a high resolution picture of the underlying complex electronic processes active in laser-produced plasmas. Thus, stringent tests of atomic theory become possible to guide the development of quantitative plasma models.

Presenting Author

Dr. José R. Crespo López-Urrutia is a staff scientist Staff scientist and group leader at Max-Planck-Institut für Kernphysik, Heidelberg.

S25

Electron and Ion Dynamics in EUV-induced Plasmas

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

[1] *Eindhoven University of Technology, Den Dolech 2, 5612 AZ Eindhoven, The Netherlands*
[2] *ASML, De Run 6501, 5504 DR Veldhoven, The Netherlands*

Plasmas induced by irradiation of a low pressure background gas with pulsed Extreme Ultraviolet (EUV) light, are strongly transient and demonstrate different fundamental processes – such as photoionization, electron-impact ionization, temperature relaxation and diffusion – being dominant at different time scales. Therefore, these so-called EUV-induced plasmas provide a scientific playground revealing the relevant plasma dynamics and the interaction of these kinds of plasmas with their environment. From an application point of view, bringing state-of-the-art knowledge to the next level is useful in terms of optimizing the design of lithography tools towards least impact of EUV-induced plasmas on the lifetime of delicate optics.

This contribution elaborates on experimental investigation of electron and ion dynamics in pulsed EUV-induced plasmas. Electron dynamics is monitored by means of single and double-mode Microwave Cavity Resonance Spectroscopy (MCRS) while an electrostatic mass quadrupole spectrometer is utilized to measure ion energy distributions. As such, these combined plasma diagnostics have brought new insights into the dynamics of pulsed EUV-induced plasmas.

Presenting Author

Job Beckers holds the position of Assistant Professor at the Applied Physics department of the Eindhoven University of Technology. He obtained his MSc and PhD [Cum Laude] degree from the Eindhoven University of Technology after which he worked in industry on the development of discharge produced plasma (DPP) EUV sources. Eventually, he accepted the position of assistant professor in the field of Complex Ionized Media in which his main research areas are: the physics of plasmas containing nanoparticles and the physics of radiation-produced plasmas.

S26

Enhancement of X-ray Emission by Double-pulse Target Ablation in a Laser-produced Plasma

Pranitha Sankar, Reji Philip

Ultrafast and Nonlinear Optics Lab, Light and Matter Physics Group
Raman Research Institute, Bangalore 560080, India

Owing to its various applications, the generation of X-rays from intense laser-matter interaction has received substantial research attention in the last decade. The high densities and temperatures possible with laser plasmas is ideal for obtaining efficient X-ray emission. Here we investigate X-ray emission in the energy range of 10 keV to 150 keV from plasmas produced by ablating high Z and low Z targets (Tungsten and Aluminium) using single and double ultrafast laser pulses (100 fs, 800 nm) of 10^{14} to 10^{15} W/cm^2 intensity. Ablation using 400 nm radiation did not show any significant enhancement in X-ray emission. To investigate the effect of double pulse ablation, the 800 nm pulse was split into two before reaching the target, such that one of the pulses could be delayed up to several nanoseconds compared to the other. A substantial enhancement in X-ray emission was observed with double pulse ablation geometry. While the observed hot electron temperature is about 20 keV for single pulse ablation, there is a five-fold increase to about 100 keV with double pulse ablation. By employing different energies and relative time delays for the two pulses, optimum conditions for X-ray generation with the highest efficiency have been determined.

Presenting Author

After obtaining a Master's degree in Physics from the University of Calicut, India, Pranitha Sankar initially worked as a Junior Research Fellow in an AISRF (Australia-India Strategic Research Fund) project at the Raman Research Institute, Bangalore on the nonlinear optical properties of nanomaterials, and later shifted her focus to the study of EUV and soft X-ray emission from metallic targets. Currently she is employed as a research assistant at the ultrafast and nonlinear optics lab of the Raman Research Institute, and is registered for a PhD degree with the National Institute of Technology, Surathkal, India. Her research interests include ultrafast spectroscopy and laser produced plasmas.

S27

Analysis of the Fine Structure of the EUV Emitting Ions $Sn^{7+...14+}$

F. Torretti[1,2], A. Windberger[1,3], A. Borschevsky[4], A. Ryabtsev[5,6], S. Dobrodey[3], H. Bekker[3], W. Ubachs[1,2], R. Hoekstra[1,7], J. R. Crespo López-Urrutia[3] and O. O. Versolato[1]

[1] Advanced Research Center for Nanolithography, Science Park 110, 1098 XG Amsterdam, The Netherlands
[2] Department of Physics and Astronomy, Vrije Universiteit, de Boelelaan 1081, 1081 HV Amsterdam, The Netherlands
[3] Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, Heidelberg, Germany
[4] The Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands
[5] Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow, Russia
[6] EUV Labs, Ltd., Troitsk, Moscow, 108840 Russia
[7] Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

The highly charged ions $Sn^{7+...14+}$ are of technological interest as these are used in laser-produced-plasma (LPP) sources for the generation of extreme ultraviolet (EUV) light for nanolithography applications. Due to the complex electronic configurations of these ions, with their open 4*d* subshells, level assignments and line identifications represent a challenge for theory and experiment. Despite the fundamental role played by these ions in EUV sources, only few studies have been dedicated to level identifications. We provide new spectral data, simultaneously recorded in both the optical and EUV regimes, obtained in a charge-state-resolved manner using an electron beam ion trap. Transitions in the lowest configurations of $Sn^{7+...14+}$ have been identified using *ab initio* Fock space coupled cluster calculations and semi-empirical calculations within the Cowan code framework. With our new experimental and theoretical work, we have shown that the line and level identifications in previous studies need to be re-evaluated [1].

[1] A. Windberger *et al*, Phys. Rev. A **94**, 012506 (2016)

Presenting Author

Francesco Torretti is a PhD candidate at the Advanced Research Centre for Nanolithography (ARCNL) in Amsterdam. His fields of study are passive spectroscopy of tin laser produced plasmas and physics of highly charged ions.

S31

Multiphysics Model of Plasma Interaction with Gas flow in EUV Source chamber

D. Astakhov[1], V. Konovalov[1,2], I. Vichev[1,2], M. Kraposhin[3], Yu. Mankelevich[1,4], V. Ivanov[1,5], I. Popov[6], A. Ziganshin[1], D. Labetsky[7], V. Medvedev[1,2], A. Yakunin[7], K. Feenstra[7]

[1] RnD-ISAN, Moscow, Troitsk, Russia
[2] KIAM RAS, Moscow, Russia
[3] Institute for System Programming RAS, Moscow, Russia
[4] SINP MSU, Moscow, Russia
[5] Institute for Spectroscopy RAS, Moscow, Troitsk, Russia
[6] ISTEQ, Eindhoven, The Netherlands
[7] ASML Netherlands B.V., De Run 6501, 5504 DR Veldhoven, The Netherlands

Presenting Author

S32

How a Laser Impact Propels, Deforms and Fragments a Liquid Drop: The Liquid Dynamics of the Pre-pulse

Hanneke Gelderblom[1], Alexander L. Klein[1], Henri Lhuissier[2], Emmanuel Villermaux[3], Dmitry Kurilovich[4], Oscar Versolato[4], Jacco H. Snoeijer[1,5] and Detlef Lohse[1]

[1] Physics of Fluids, Faculty of Science & Technology, University of Twente, The Netherlands,
[2]IUSTI - Aix-Marseille Universitie, France, [3]IRPHE - Aix-Marseille Universitie, France,
[4]Advanced Research Centre for Nanolithography, The Netherlands,
[5] Mesoscopic Transport Phenomena, Department of Applied Physics, Eindhoven University of Technology, The Netherlands

Control of the mass distribution of a liquid tin drop during the pre- pulse is of key importance to improve the EUV source performance. Indeed, the final drop shape and its stability have a strong influence on the conversion of liquid tin to plasma and the amount of debris formed. To understand how the drop deformation depends on the laser-pulse properties, detailed knowledge on the liquid dynamics of the pre-pulse is required. In this work, we focus on the fundamental liquid dynamic response of a liquid drop hit by a ns laser pulse. The deposition of laser energy in a superficial layer of the free-falling drop leads to propulsion, strong deformation and eventually fragmentation of the drop. We reveal the detailed drop dynamics by combining high-speed and stroboscopic imaging with analytical modelling. The propulsion speed and the time-deformation law of the drop are measured and explained in terms of the laser-pulse energy, laser focus, and the liquid properties. We investigate how ligaments and holes develop on the deforming drop, which eventually results in its fragmentation and identify the dependence of this fragmentation process on the laser-pulse properties.

Presenting Author

Hanneke Gelderblom obtained her PhD degree in the Physics of Fluids group at the University of Twente. Her research focusses on the fluid motion inside droplets during e.g. evaporation, impact and spreading, liquid fragmentation, and solidification. She is currently working as a scientific project leader of the project "Fundamental fluid dynamics challenges in Extreme Ultraviolet Lithography", which is a collaboration between the Physics of Fluids group at the University of Twente, ASML, and the Dutch Foundation for Fundamental Research on Matter (FOM).

S33

Simulating EUV Generation in Laser-Produced Plasma

Howard Scott[1] and Frank McQuillan[2]

[1]Lawrence Livermore National Laboratory, Livermore, CA, USA
[2]School of Physics, University College Dublin, Belfield, Dublin, Ireland

Radiation-hydrodynamics simulations of radiative emission from laser-produced plasmas require modeling multiple macroscopic physical processes with an accurate treatment of the underlying atomic physics. Basic temperature, density and spatial scales follow from the laser parameters and material properties, determining the general computational approach, but capturing important features with high fidelity and matching experimental diagnostics often calls for specialized techniques.

We discuss experiences with and developments from simulations of EUV generation done at LLNL and UCD over the last few years. Common goals of these efforts included identifying critical physical processes and developing a predictive modeling capability. The modeling at UCD used Cretin [1] for 1D simulations of Sn plasmas driven by Nd: YAG and CO2 lasers. The LLNL modeling, done in collaboration with Cymer, used HYDRA [2] for a series of 1D, 2D and 3D simulations of Sn droplets driven by a CO2 laser prepulse and main pulse.

[1] H. A. Scott, J. Quan. Spectrosc. Radiat. Transf. **71**, 681 (2001).
[2] M.M. Marinak, G.D. Kerbel, N.A. Gentile, O. Jones, D. Munro, S. Pollaine, T.R. Dittrich, S.W. Haan, Phys. Plasmas **8**, 2275 (2001).

This work performed under the auspices of U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Presenting Author

S34

Application of Plasma Formation Modeling for LPP EUV Sources

Michael Purvis[a], Alexander Schafgans[a], Daniel Brown[a], Igor Fomenkov[a], Rob Rafac[a], Josh Brown[a], David Brandt[a], Harry Kreuwel[b], Andrei Yakunin[b], Aaron Fisher[c], Howard Scott[c], , Dave Eder[c], Scott Wilks[c], Anthony Link[c], Jave Kane[c], Fred Hartemann[c], Alice Koniges[d], Kevin Gott[d], Steve Langer[c]

[a]Cymer LLC, 17075 Thormint Ct, San Diego, USA
[b]ASML Netherlands B.V., De Run 6501, 5504 DR Veldhoven, The Netherlands
[c] Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550, USA
[d] Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720, USA

We present an overview of plasma simulation activities performed in collaboration with Lawrence Livermore National Labs and other institutions. This modeling is performed to advance the rate of learning about optimal EUV generation for laser produced plasmas and to provide insights where experimental results are not currently available, helping to drive source performance scaling in support of the EUV Lithography roadmap. The model simulates pre-pulse laser interaction with the tin droplet and follows the droplet expansion into the main pulse target zone. Next, the simulated target is transferred into a plasma physics code where the interaction of the expanded droplet with the main laser pulse is simulated. We will review aspects of the codes physics that were found to be critical to accurately predicting EUV conversion efficiency and plasma formation. We demonstrate the predictive nature of the code and provide comparison with experimental results.

Presenting Author

Michael Purvis serves as the Systems Power Architect for the EUV Source Program at ASML San Diego, whose focus is power scaling. Over the last decade, Michael has published seminal papers in the field of laser created plasmas. His initial investigations at Colorado State University included developing discharge and laser produced soft x-rays lasers for applications in plasma diagnostics, after which he worked on theoretical plasma modelling and high energy density experiments at CSU, Lawrence Livermore National Labs and SLAC. He is now applying his broad knowledge of plasmas generated in the femtosecond to nanosecond time scales towards the development of EUV light sources at ASML.

S41

Fiber Laser - driven High Harmonic Generation as Powerful Source for Applications

Steffen Hädrich[1], Jan Rothhardt[2,3], Jens Limpert[2,3,4]

[1]Active Fiber Systems GmbH, Wildenbruchstraße 15,07745 Jena, Germany
[2]Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Albert-Einstein-Straße 15, 07745 Jena, Germany
[3]Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena, Germany
[4]Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Straße 7, 07745 Jena, Germany

Table-top coherent XUV sources are a viable alternative to large-scale facilities such as synchrotrons and free electron lasers. This can be achieved via high harmonic generation (HHG) of ultrashort pulses. Due to the inherently low conversion efficiency and the low average power of the frequently used Ti:Sapphire lasers the generated number of photons in the desired XUV spectral range is limited. A significant increase in repetition rate and average power of HHG sources is necessary to extend their applicability, in particular, to (multi-dimensional) photoemission spectroscopy and microscopy, coincidence-based detection schemes or nano-scale imaging.

In this contribution recent advances in high average power XUV sources based on HHG with state-of-the-art fiber laser systems will be presented. Phase-matching aspects will be discussed and finally be implemented to efficiently convert 100 W class ultrashort laser pulses to photon energies ranging from 20-300eV. The achieved average power level can be in the milliwatt (at 21eV), 100µW (30eV) and few-µW range (up to 70eV) surpassing existing sources by up to an order of magnitude. First cutting edge research applications, including nano-scale imaging with 15nm resolution, are presented. Furthermore, it will be outlined how these sources are currently being transferred into industrial grade user systems.

Presenting Author

Steffen Hädrich was born in Jena, Germany, on August 2, 1982. He received the Diploma degree in general physics and the Ph.D. degree from the Friedrich- Schiller-Universität Jena, Jena, Germany, in 2007 and 2012, respectively. From 2012 to August of 2016 he was a Postdoctoral Researcher at the Institute of Applied Physics, Friedrich- Schiller-Universität Jena. His research interest was focused on high average power ultrashort pulse fiber lasers, pulse compression, nonlinear optics and high harmonic generation. In September 2016 he joined active fiber laser systems GmbH in Jena to develop ultrashort, few-cycle laser systems and XUV sources.

S42

Enhancement of Extreme-Ultraviolet Fluorescence and Localized High Harmonic Generation using Structured Solids

Murat Sivis

4th Physical Institute - Solis and Nanostructures, Georg-August University, Göttingen, Germany

The localized enhancement of femtosecond light fields in tailored metal or semiconductor nanostructures is a formidable approach to study highly nonlinear phenomena, such as multiphoton extreme-ultraviolet (EUV) fluorescence or high harmonic generation (HHG). Two recent examples for the enhancement of EUV emission in nanostructures will be discussed in this talk.

The plasmonic enhancement of highly nonlinear gas excitations in gold bow-ties and hollow waveguides leads to the emission of EUV light[1-5]. However, contrary to reports indicating HHG in such structures[1,2], these approaches have been proven to enhance incoherent EUV fluorescence exclusively[3-5]. Here, we will present our comprehensive experimental findings, which will clarify important aspects of EUV light generation in plasmonic nanostructures.

In the second part of the talk, enhanced HHG in semiconductor structures is presented. Our recent experimental results[6] illustrate the high potential of imaging localized HHG, which is induced by local geometrical, structural or electrical changes in the solid crystal. The possibility of spatially resolved HHG in solids adds another degree of freedom to the ongoing advances in all-optical solid state spectroscopy[7,8].

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[3] Sivis, M., *et al.* Nanostructure-enhanced atomic line emission. *Nature* **485**, E1-E3 (2012).
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[5] Sivis, M., & Ropers, C. Generation and bistability of a waveguide nanoplasma observed by enhanced extreme-ultraviolet fluorescence. *Phys. Rev. Lett.* **111**, 085001 (2013).
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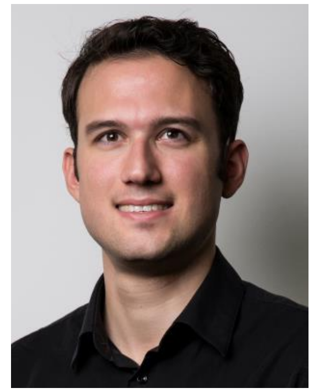
[7] Luu, T. T. *et al*. Extreme ultraviolet high-harmonic spectroscopy of solids. *Nature* **521**, 498-502 (2015).
[8] Vampa, G. *et al*. Linking high harmonics from gases and solids. *Nature* **522**, 462-464 (2015).

Presenting Author



Dr. Murat Sivis graduated with a diploma in physics from the University of Göttingen, Germany in 2009. His diploma thesis was on growth and characterization of two-dimensional electron gases in AlGaN/GaN heterostructures. From 2009 to 2013, he did his PhD degree in physics in the group of Prof. Claus Ropers at the University of Göttingen, Germany. His PhD work was on extreme-ultraviolet light generation in plasmnonic nanostructures. After completing his PhD with the highest distinction (summa cum laude), he continued his research on highly nonlinear EUV light generation and photoemission in plasmonic nanostructures until now. In 2014, he was awarded with the Dr. Berliner-Dr. Ungewitter prize for the best dissertation and received the award for outstanding young academics publications from the foundation board of the University of Göttingen. In 2016, he visited the group of Prof. Paul Corkum at the National Research Council Canada in Ottawa, where he conducted experiments on high harmonic generation in structured semiconductors.

S43

Applications of a Table-top Laser Driven EUV/Soft X-ray Source and Wavefront Optimization at Short Wavelengths

K. Mann, J.O. Dette, M. Lübbecke, T. Mey, M. Müller, B. Schäfer

Laser-Laboratorium Göttingen e.V., D-37077 Göttingen, Germany

The progress in development of laboratory-scale soft x-ray sources has enabled experimental techniques that could be performed before almost exclusively at synchrotrons. In this contribution various metrological applications of a compact and long-term stable laser-driven plasma source emitting in the extreme UV and soft x-ray range are presented. Based on a pulsed gas jet target, the system produces clean radiation in the spectral region from 1 to 20nm. Broad-band emission from a Kr plasma is used for polychromatic absorption spectroscopy in the ´water window´, probing the fine-structure of K- or L-absorption edges of various elements (e.g. C, N, O, S, K, Ca, Mn, Fe, Cu). The performance of this NEXAFS spectrometer for chemical analysis is demonstrated for a variety of different organic and inorganic samples. Moreover, monochromatic radiation at a wavelength of 2.88nm produced from a nitrogen plasma is employed for soft x-ray microscopy, accomplishing a spatial resolution of 50nm.

The imaging performance of short wavelength optics is characterized with the help of a Hartmann-type wavefront sensor developed for the EUV/soft x-ray range. In various co-operations this device is applied for actinic fine-tuning of beam line focusing optics of free electron lasers and synchrotrons. Wavefront aberrations introduced by optics misalignment can be strongly reduced, leading to smaller foci and enhanced peak intensities.

Presenting Author

Dr. Klaus Mann is Head of Department of “Optics / Short Wavelength" in Laser-Laboratorium Göttingen e.V.

S44

Unresolved Transition Array (UTA) Emission from Highly - charged Ions in Heavy-element Plasmas by a Dual-laser Pulse Irradiation

Takeshi Higashiguchi

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

Light sources based on spectral emission from unresolved transition arrays (UTAs), which originate from the highly charged ions in heavy element plasmas are of great interest in fundamental research and for industrial applications, such as extreme ultraviolet (EUV) lithography for future integrated circuits, laser-driven water window soft x-ray (SXR) sources for single shot imaging of biological cells *in vivo*, and material sciences. UTA emission can provide high output power with high conversion efficiency of laser input energy to EUV or soft x-ray emission because the transitions responsible. In fact, such UTA emission at a wavelength of 13.5 nm from LPP EUV sources with high average power and a conversion efficiency greater than 4% based on highly charged tin (Sn) plasmas are currently used for EUV lithography. UTA emission from n = 4 - n = 4 (□n = 0) transitions in LPPs of other higher-Z elements occur at wavelengths that can be used for other applications such as soft x-ray microscopy (SXM) in the water window SXR region from 2.3 to 4.4 nm and the carbon window which lies between 4.4 and 5 nm. We have shown that the strong resonance UTAs emitted by Nd: YAG laser-produced plasmas of high-Z elements ranging from $_{50}$Sn to $_{83}$Bi obey a quasi-Moseley's law. Laser-produced bismuth (Bi) plasmas are one of the candidates for a water window SXR source, and consequently their spectrum has been recently analyzed.

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 light sources and microscope, hybrid short pulse laser system, and advanced optics for vector wave generation.

S45

Study of Plasma Dynamics and Spectral Tunability in Hollow - cathode Triggered Gas-discharge Sources

Florian Melsheimer [1,2,4], Malte Ranis [1,2,4], Daniel Wilson [1,2,3], Sophia Schröder [1, 2, 4]
and
Larissa Juschkin [1,2,4]

[1] Forschungszentrum Jülich, Peter Grünberg Institut (PGI-9), Germany
[2] RWTH Aachen University, Experimental Physics of EUV, Aachen, Germany
[3] Forschungszentrum Jülich, Peter Grünberg Institut (PGI-6), Germany
[4] Jülich-Aachen Research Alliance (JARA), Fundamentals of Future Information Technology, Germany

Gas discharge EUV sources are compact and versatile sources of short wavelength radiation for small-scale applications. By employing different gases as well as gas-mixtures, the emission properties can be tailored according to the application requirements. Spectral analysis for a variety of settings and fuels is performed to explore the parameter range for future experiments. Inherent to gas-puff z-pinches, not only spectra but also the plasma dynamics change with gas type and pressure. Time resolved plasma images have been recorded with use of a CsI-coated microchannel plate (5-30 nm spectral rage) at 2 ns exposure time and in 5 ns time steps under different observation angles. This technique is used to create "slow motion" representations of discharges in different gases and gas mixtures.

Detailed knowledge of pinch dynamics is essential for the current development of high-brightness short-wavelength sources. The gained knowledge about the influence of fuel, pressure and discharge voltage on the spectrum is especially important for applications requiring spectral tunability like EUV-based photoelectron spectroscopy and microscopy or element selective imaging.

Presenting Author

Florian Melsheimer is a PhD student at Rheinisch Westfälisch Technische Hocheschule, Aachen in the area of EUV Source development based on a CO_2-laser heated z-pinch gas discharge. From 2013 to 2016, he was a Master of Science student at the same institute. The title of his thesis was "Characterization and synchronization of z-pinch gas discharge and Nd:YAG laser for improved EUV light generation."

S46

Laser-produced Highly-ionized Aluminum Plasma for High Harmonic Generation

N. Smijesh[1], Kavya H. Rao[1], N. Klemke[1], R. Philip[2], I. Litvinyuk [1] and R. T. Sang [1]

[1]Australian Attosecond Science Facility, Centre for Quantum Dynamics, Griffith University Nathan, QLD-4111, Australia
[2] Ultrafast and Nonlinear Optics Lab, Light and Matter Physics Group, Raman Research Institute, Bangalore 560080, India

The properties of laser produced plasmas (LPP), which depend on laser parameters such as pulse duration, energy, spot size and wavelength, and also on material properties and ablation conditions, can be tailored for a multitude of applications. In the present work, using 1064 nm, 7 ns pulses from an Nd:YAG laser, a highly ionized aluminum plasma is generated, which is optimized for the purpose of extending the cut-off energy of high harmonic generation. The plasma is attuned spatio-temporally for Al IV emissions with irradiation energy as the control parameter using time-resolved optical emission spectroscopy. The ionization potential for Al IV being as high as ~120 eV, high harmonic radiation of energies greater than what is currently available (the highest cut-off energy achieved to date is 1.6 keV from Helium by using 3.9 µm, 80 fs laser pulses) can be generated by properly utilizing such a plasma source. Work in this direction can radically improve the energy range of LPP X-ray sources available with typical laboratories so that the dependence on large external facilities such as synchrotrons can be potentially minimized.

Presenting Author

Prof. Reji Philip is currently the Coordinator of the Light and Matter Physics (LAMP) Group at the Raman Research Institute (RRI), Bangalore, India. After post-doctoral studies at the University of Regensburg, Germany and Tata institute of fundamental research, Mumbai, he joined RRI in year 2000 as a faculty member. He has mentored several doctoral students and post-docs, and has about 150 publications in reputed international journals, and three book chapters, to his credit. He is also a co-author of *A Textbook of Nanoscience and Nanotechnology*, published by Tata McGraw Hill. He has held Visiting Scientist positions at the University of Massachusetts, Boston, and at the University of Central Florida, Orlando. He is a regular reviewer to scientific publishers such as the American Institute of Physics, American Chemical Society, Royal Society of Chemistry, and Elsevier. He has been an organizing committee member of several national and international conferences. Prof. Philip's research interests are in Laser-induced plasmas, Ultrafast Laser Spectroscopy, and Nonlinear Optics of Nanostructured Systems.

S47

Alternative Emitters for LPP sources around 6.x nm

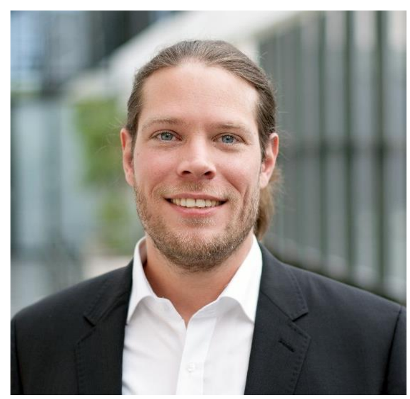
Alexander von Wezyk, Klaus Bergmann

Fraunhofer Institute for Laser Technology, Steinbachstr. 15, 52074 Aachen, Germany

For laser-produced-plasmas (LPP) with emitter materials gadolinium (Gd) or terbium (Tb) as potential target materials for the next generation of EUV-lithography at 6.x nm for HVM as well as metrology sources, one of the main challenges will be the high melting point (T_m > 1300°C) which will make it difficult to get liquid droplets or with liquids wetted surfaces as regenerative target systems, which are mandatory for sources to be used commercially.

Based on this issue aluminum (Al), magnesium (Mg) and a Gd based alloy with drastically reduced melting point (T_m < 500°C) are investigated as alternative targets and compared to pure Gd and Tb based plasmas. The results are generated by theoretical considerations based on the radiation transport inside the plasma. Instead of emission resulting from unresolved transition arrays (UTA's) at Gd/Tb emission Al and Mg shows a number of line transitions around 6.x nm. Due to the small bandwidth of available multilayer mirrors (ML) line emitters also seem to be suitable, if the emission origins from optically thick plasmas. The theoretical results are compared to experimental results done at basic experiments on solid targets.

Presenting Author



Alexander v. Wezyk received the M. Sc. Degree at the university of applied sciences of Koblenz in 2011. Since 2011, he is PhD student at the University of Technology, Aachen, Germany, and scientist at the Department for Plasma Technology, Fraunhofer Institute for Laser Technology. The technological topics are the investigations of gas discharged and laser produced plasmas for EUV-sources.

S48

Picosecond Laser Krypton Plasma Emission in Water-Window Spectral Range

P. Vrba[1], M. Vrbova[2]

[1]Institute of Plasma Physics, Czech Academy of Sciences, 182 00 Prague 8, CR
[2]Czech Technical University, Faculty of Biomedical Engineering, 272 01 Kladno, CR

Laser plasma created in krypton gas puff target is studied as a source of radiation in the water window spectral range. Spatial development of plasma induced by Nd:YAG laser pulse (170 ps/480 mJ) with peak power density 1014 W cm-2, incident on the gas-puff target is modeled using 2D RMHD code Z* [1]. The plasma is quickly heated and the critical electron density is achieved at the leading edge of the laser pulse. The time dependences of plasma electron temperature and electron density in representative points are introduced into kinetic code FLYCHK [2] as history files. The time dependences of the relative krypton ion populations proved that mainly Kr XVII - XXIV ions are responsible for emission in water window range. The instantaneous spectra during and after the application of laser pulse are presented. The most intensive spectral lines were identified. The line emission in the water-window range is observed 0 ps - 800 ps delayed after the laser peak. Evaluated time dependent spectra and time integrated spectra measured [3] correspond each other. The krypton laser plasma heated to ~150 eV may be also considered as a possible candidate for source of water window radiation [4].

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Presenting Author

Pavel Vrba is senior researcher at the Institute of Plasma Physics of Czech Academy of Sciences in Prague. His current research activities are computer simulations of water window capillary radiation sources, capillary discharge pre-ionization, wave guiding of high intensity short pulses in capillary discharge and gas puff laser plasmas.

S51

Multilayer and Thin film Coatings for EUVL and Beyond

I.A. Makhotkin, D.S. Kuznetsov, R.A.J.M. van den Bos, R. Coloma Ribera, S.P. Hendrikx, A. Zameshin, J. M. Sturm, C.J. Lee, R.W.E. van de Kruijs, A. Yakshin, E. Louis and F. Bijkerk

MESA+ Institute for Nanotechnology, University of Twente, Netherlands

Continuous demand for improvement of reflectance and stability of optical coatings for 13.5 nm, 6 nm and shorter wavelengths requires extensive research on the physics and chemical aspects of these coatings. In order to reach the ultimate reflectivity and optics lifetime we are continuously working on a deeper understanding of the synthesis and the usage aspects, including the development of analytical techniques and numerical approaches to the characterization of thin films and multilayers. In this talk, we will present our latest results on the development of coating and metrological approaches.

For many optical coatings, including freestanding membrane optics, it is required to grow ultrathin closed layers. To determine the minimum thickness of a coating required to form a closed layer, high-sensitivity low energy ion scattering (HS-LEIS) was used. This technique has the ultimate sensitivity to atomic composition of the outermost surface layer. The HS-LEIS study of Ru films grown on various substrates will be discussed [1]. For the optimization of multilayer growth in-house diagnostics of multilayer structures is required. Grazing Incidence X-ray Reflectivity (GIXR) can provide essential feedback but it's application is limited due to an ambiguous data analysis procedure. To simplify the GIXR data analysis we have developed a model-free approach, with reduced assumptions about layers and interfaces. The study of the structure of LaN/B multilayers [2] with this model-free GIXR showed much enhanced sensitivity to the concentration profile of interfaces of periodic multilayer structures [3]. For successful application of an optical coating, "just" demonstrating high reflectivity and throughput is not enough. The coating has to survive the required operational regimes, including periodic cleaning to remove contaminants. Cleaning is often performed using hydrogen radicals and ions and surface blisters may appear, which irreversibly damage the mirror surface. To understand the nature of blister growth we have built an elastic model that predicts many characteristic features of blisters [4].

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2. Kuznetsov, D.S., et al., *High-reflectance La/B-based multilayer mirror for 6.x nm wavelength.* Optics Letters, 2015. **40**(16): p. 3778-3781.
3. Zameshin, A., et al., *Reconstruction of interfaces of periodic multilayers from X-ray reflectivity using a free-form approach.* Journal of Applied Crystallography, 2016. **49**(4): p. 1300-1307.
4. van den Bos, R.A.J.M., et al., *A model for pressurized hydrogen induced thin film blisters.* To be published, 2016.

Presenting Author

S53

A Study of EUV/SXR Grazing Incidence Collectors for Metrology Sources

Ladislav Pina[1] and Andrzej Bartnik[2]

[1]Czech Technical University, Prague
[2]Institute of Optoelectronics, Military University of Technology, Warsaw

EUV/SXR grazing incidence rotationally symmetric collectors for metrology sources were studied theoretically and experimentally. Computer modeling (ray-tracing) of selected collectors and experimental results with laboratory sources are presented. Spectral reflection for different mirror coating materials was measured.

Presenting Author

S54

EBL2: Versatile EUV Exposure and Analysis facility

E. (Edwin) te Sligte, N. B. Koster, F. T. (Freek) Molkenboer,
P. (Peter) van der Walle, P. M. (Pim) Muilwijk, W. F. W. (Wouter) Mulckhuyse, B.W. (Bastiaan) Oostdijck, C.L. (Christiaan) Hollemans, J. (Jeroen) Westerhout, B. A. H. (Bjorn) Nijland, P.J. (Peter) Kerkhof, M. (Michel) van Putten,
A. M. (André) Hoogstrate, A. F. (Alex) Deutz,

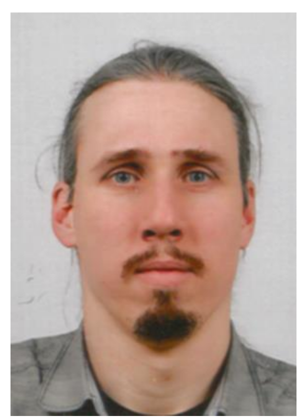
TNO; Stieltjesweg 1,2628 CK Delft -The Netherlands

TNO is building EBL2 as an independent research and test facility for the EUV industry to address lifetime and functionality issues. EBL2 will enable tests consisting of EUV exposures and analysis on small samples, photomasks, pellicles, and other components. The high power EUV exposures will be customizable in EUV irradiation properties, gas environment, and sample temperature; available analysis techniques include real-time in-situ ellipsometry and X-ray Photoelectron Spectroscopy (XPS).

The design of EBL2 is based on the architecture of the EBL system that has been operational at TNO since 2005. The system consists of a beam line which irradiates the sample under controlled conditions, and an XPS module that analyses the surface composition of a sample. Photomasks and smaller samples are transferred to and between these modules by an automated handling module that maintains NXE compatibility for photomasks provided in dual pods. For applications requiring low EUV power, a separate metrology output port is available on the Sn-fueled Ushio EUV source.

This contribution will provide an overview of the system design and report on the progress of its construction. In addition, application of EBL2 to reticle lifetime testing, lifetime testing of EUV optical components, and fundamental research will be discussed.

Presenting Author



Contamination control expert Edwin te Sligte studied Applied Physics at the Eindhoven University of Technology and obtained his PhD in Atomic Physics in 2005 from the Eindhoven University of Technology. During the last 11 years he worked at TNO on numerous customer confidential projects on cleaning, contamination control, and optics degradation mechanisms in EUV scanners and sources, from Alpha Demo Tools to current NXE models.

S61

Recent Activities at FLASH and European XFEL

M. V. Yurkov

DESY, Hamburg

Two x-ray FEL user facilities are located in Hamburg: FLASH and European XFEL. Both x-ray lasers are driven by superconducting linear accelerators operating in a burst mode. Energy of accelerator is 1.25 GeV for FLASH, and 17.5 GeV for the European XFEL. FLASH produced first light in the year 2000, and it is the first x-ray FEL user facility. It is equipped with two undulator beamlines, and covers radiation wavelengths from 60 nm down to 4 nm in the fundamental (1.6 nm in the harmonics). European XFEL entered its final construction stage, and the first beam is expected in the end of 2016, with first user experiments in 2017. European XFEL will cover wavelength range from 6 nm down to 0.05 nm. This report will present an overview of current activities at FLASH and European XFEL.

Presenting Author

S62

Strategy to Realize the EUV-FEL High-power Light Source: Present Status on the EUV-FEL R&D Activities

Hiroshi Kawata

High Energy Accelerator Research Organization (KEK)
Tsukuba, Ibaraki 305-0801, Japan

It is important to develop the high power EUV light source up to 1 kW to realize the 5nm node, which is expected to be in production at 2023-24. To this end, an energy recovery linac(ERL)-based free electron laser(FEL) must be a most promising candidate, so that our group has done some feasibility studies from the view point of accelerator technology. However, this kind of design studies by academia would not be enough to realize the EUV-FEL light source for semiconductor industry. It is required to conduct the R&D on the design of such practical accelerators in collaboration with equipment suppliers and end users. Furthermore, because the properties of the FEL light are somewhat different from these of an ordinal LPP light source, feasibility studies for EUV light optics, multi-layer-mirrors, masks, and resist materials, and so on, will be required. Thus, it is important to make a collaborative work between source group, tool and material suppliers, and end users to realize the EUV Lithography total system by means of EUV-FEL light source. According to these requirements, the EUV-FEL Light Source Study Group for Industrialization has been established since last year (2015). At the conference, the activities will be presented.

Presenting Author

Hiroshi Kawata is the Head of ERL Project Office in KEK, Department of Future Accelerator and Detector Technologies, High Energy Accelerator Research Organization (KEK).

S63

Linear and Non-linear Interaction of X-ray Free Electron Laser Radiation with Materials

Hermann A. Dürr

SLAC National Accelerator Laboratory, Menlo Park CA 94025, USA and Van der Waals – Zeeman Institute, University of Amsterdam, Science Park 904 C4 23, 1098XH Amsterdam, The Netherlands

Femtosecond x-ray pulses from free electron laser sources offer the unique opportunity to stroboscopically track the nanoscale motion of electrons and spins in functional materials either via real-space holographic imaging [1] or reciprocal-space scattering techniques [2,3]. However, the simultaneous presence of many indistinguishable, coherent photons also offers for the first time the possibility to investigate non-linear phenomena such as x-ray induced transparency of materials [4]. The observed disappearance of the diffraction pattern of the circular XFEL beam with increasing x-ray fluence [4] indicates that the non-linear x-ray interaction with matter can even alter the XFEL beam properties opening up new ways to overcome the single-photon diffraction limit.

[1] T. Wang, et al., Rev. Lett. **108**, 267403 (2012).
[2] S. de Jong, et al., Nature Materials **12**, 882 (2013).
[3] C. E. Graves, et al., Nature Materials, **12**, 293 (2013).
[4] B. Wu, et al., Phys. Rev. Lett. **117**, 027401 (2016).

Presenting Author

S71

Coherent Diffraction Imaging with Partially-coherent Discharge Plasma based EUV Sources

Larissa Juschkin[1,2], Jan Bußmann[1,2], Michal Odstrcil[1,3], Raoul Bresenitz[1], Yusuke Teramoto[4], Marco Perske[5], Torsten Feigl[5], William S. Brocklesby[3]

[1] Chair for Experimental Physics of EUV, JARA-FIT, RWTH Aachen University, Steinbachstrasse 15, 52074 Aachen, Germany
[2] Peter Grünberg Institute 9, JARA-FIT, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
[3] Optoelectronics Research Center, University of Southampton, SO17 1BJ, United Kingdom
[4] BLV Licht- und Vakuumtechnik GmbH, Steinbachstraße 15, Aachen, Germany
[5] OptiXfab. GmbH, Hans-Knoell-Str. 6, 07745 Jena, Germany

Coherent diffraction imaging (CDI) is a powerful method with a broad range of applications in nanoscience, material science and biology. It offers a possibility of either avoiding the imaging optics or including their limited quality into the image reconstruction process. Additionally, it allows for recovering both phase and amplitude of the exit-wave field behind the sample. This results in much higher contrast for phase objects that would have otherwise low contrast in standard bright field microscopy. We report on lens-less imaging experiments including also scanning probe (ptychographic) CDI with compact plasma radiation sources developed for EUV lithography applications. Two kinds of discharge sources have been used in experiments, a hollow cathode triggered pinch plasma source operated with oxygen and a laser assisted discharge EUV source with a liquid tin target. The CDI reconstructions of different samples were achieved by applying constraint relaxation to the CDI algorithm. The developed linear relaxation method can handle the low spatial coherence and broadband nature of the source radiation as well as the residual background due to visible light emitted by the plasma. The resolution down to 100 nm is demonstrated and is limited presently by the sample structure contrast and exposure time. Our results show that compact plasma-based EUV light sources of only partial coherence can be effectively used for lens-less imaging applications. In the outlook, we propose an experiment for CDI using a reflective setup and a compact xenon-discharge based EUV source. Our special focus is put on demonstration of actinic diagnostics of multilayer mirrors modified by programmed, buried defects. Coherent diffraction imaging can recover the phase and amplitude change induced by the buried defects. This information is not accessible by other methods or at other inspection wavelengths and facilitates further development and improvement of the ML fabrication process.

Presenting Author

S72

Transient XUV and X-ray lasers pumped by Free-Electron Laser Sources

N. Rohringer

Max Planck Institute for the Structure and Dynamics of Matter
Hamburg, 22761, GERMANY

The dream of realizing a laser in the XUV and x-ray wavelength regime is as old as the optical laser itself, and a first suggestion of a possible concept for a short-wavelength laser dates back to a seminal paper published in 1967 [1]. The proposed scheme suggests ionization of inner-shell or core electrons by a broadband radiation source that is tuned above the absorption edge of an inner shell. If inner-shell ionization rates are comparable to the natural decay rates of the created inner-shell holes, i.e. Auger or fluorescence rates, a population inversion on a valence to inner-shell transition can be established in that transiently core excited plasma that can lead to stimulated emission and strong amplification gain. To overcome the fast decay rates of the core holes, it needs, however, intensities ranging from 10^{18}-10^{20} W/cm^2, to achieve lasing on a transition in the nm or Å wavelength region. These intensities are achievable at present day x-ray free electron laser sources and allowed for the first realization of an atomic inner-shell x-ray laser in Neon gas [2], showing saturated amplification of the Ne K-□ transition at 1.45 nm. Here, we present results of amplified spontaneous K-□ emission at a wavelength of 2.9 Å in Manganese salts in aqueous solutions [3] with highly focused XFEL beams. Coherent amplification of the Mn K-□ emission by four orders of magnitude and saturation of the signal has been demonstrated in $MnCl_2$ one-molar solution. More excitingly, the chemical shifts of $MnCl_2$ and $KMnO_4$ aqueous solution is maintained in the strongly spectrally sharpened stimulated K-□ emission spectra and coherent amplification has been shown at lower concentration. Besides the fundamental interest in developing the shortest, transform limited pulses in the x-ray domain – the produced pulses have estimated pulse durations below a femtosecond, our finding has implications on x-ray emission spectroscopy, allowing for spectrally sharpened single-shot measurements in optical/x-ray pump probe experiments.

The realization of transient XUV lasers proceeds along a different path and population inversion is achieved in sequential process by an inner-shell photoionization process followed by Auger decay of the ion [4]. In our recent work we revisit an Auger-decay pumped x-ray lasing scheme in Xe and Kr, that was previously studied using plasma-based, broad-band radiation source [5]. Tuning the 50 fs long FEL pulses to the giant resonance of the 4d (3d) ionization in Xe (Kr) results in the creation of an inner-shell hole that decays via Auger decay to Xe (Kr) doubly charged ions. Different Auger decay channels result in the creation of a population inversion in the residual doubly charged ions and strong amplified spontaneous emission is observed. In Xe three strong lasing lines were observed at 65 nm, 68 nm and 109 nm, whereas Kr shows strong gain at 54 nm, and amplification over 4 orders of magnitude up to saturation was observed. In a second experiment, the Xe and Kr gas was gradually condensed to form an ensemble of clusters. We will present experimental results of XUV lasing in Xe and Kr clusters of changing cluster size and discuss strong differences to lasing in the homogeneous Xe and Kr gas medium.

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[4] E. J. McGuire, Phys. Rev. Lett. 35, 844 (1975).
[5] H. Kapteyn, R. W. Lee, and R. W. Falcone, Phys. Rev. Lett. 57, 2939 (1986).

Presenting Author

Since 2015, N. Rohringer is the group leader at the Max Planck Institute for the Structure and Dynamics of Matter. In 2005 she received her PhD in Theoretical Physics at the Vienna University of Technology

S73

Water-Window X-Ray Pulses from a Laser-Plasma Driven Undulator

Andreas R. Maier

Center for Free-Electron Laser Science & Department of Physics, Hamburg University

Laser-plasma accelerators are prominent candidates for driving next-generation light sources. The generated few-fs x-ray pulses from the undulator can be perfectly synchronized to other secondary sources (for example: THz) driven by the same master laser, enabling a hyper-spectral source and pump-probe experiments with unprecedented temporal resolution.

We report on experimentally demonstrated undulator radiation from a laser-plasma accelerator, with photon pulses tunable over a range from 100 to 300 eV. We will present our current activities in merging the laser-plasma technology with conventional accelerator technologies towards robust performance. Finally, we will discuss the path towards higher repetition rates and average powers, and possible developments towards a plasma-driven water-window free-electron laser.

Presenting Author

S74

Optimization of Laser-produced Plasma towards the Generation of High-order Harmonics

N. Smijesh*, Kavya H. Rao, D. Chetty, R. T. Sang and I. Litvinyuk

Australian Attosecond Science Facility, Centre for Quantum Dynamics, Griffith University Nathan Campus, QLD-4111, Australia.

The emission and expansion features of a picosecond laser produced plasma is experimentally investigated using optical emission spectroscopy and time-resolved imaging techniques. Emission from plasma indicates the abundance of Al I, Al II, Al III and Al IV and plume is a mix of these species at the earlier stages of expansion. Emission from Al III is found to maximize at a space ~ 1 mm above the target for ~ 40 ns after being irradiated. Also, a large spatial extension of Al III emission is found in the plume, which can be attributed to the collisional excitations. On the other hand, the plasma expansion indicate adiabatic nature, where in the plume appears to split to into two components, the fast and the slow moving with velocities ~ 35 km/s and 6 km/s respectively. The space and time resolved studies are resorted to the optimization of space and time at which the plasma would be irradiated with a suitable ultrashort pulse for HHG applications.

Presenting Author

Dr. Smijesh N. Achary is currently a post-doctoral research fellow at the Centre for Quantum Dynamics of the Griffith University, has completed his doctoral studies from the National Institute of Technology Calicut, India. He holds a Master of Science degree in physics as well as a Master of Technology degree in Electronics and Communication from the Mahatma Gandhi University and The University of Kerala, India respectively. His areas of research include nonlinear optics, intense light-matter interaction, laser produced plasmas and High-order harmonic generation. Currently he is working (as a Principal Investigator) on the project on the generation of bright and coherent EUV/X-ray generation using highly-ionized laser produced plasma.

S81

Transmission Grating Spectrometer for Broadband Characterization of EUV Sources

Muharrem Bayraktar[1], Bert Bastiaens[2], Caspar Bruineman[3], Boris Vratzov[4] and Fred Bijkerk[1]

[1] Industrial Focus Group XUV Optics, MESA + Institute for Nanotechnology, University of Twente, The Netherlands
[2] Laser Physics and Nonlinear Optics, MESA + Institute for Nanotechnology, University of Twente, The Netherlands
[3] Scientec Engineering, The Netherlands
[4] NT&D – Nanotechnology and Devices, Germany

Emission from extreme ultraviolet (EUV) light sources for lithography and metrology applications needs to be maximized in a narrow wavelength band. On the other hand, these sources also emit radiation outside this wavelength band, extending into the deep ultraviolet (DUV) and visible/IR range. To gain a comprehensive understanding of the source conditions, characterization of the in-band as well as the out-of-band radiation is needed. Here, we present a broadband spectrometer based on a set of free-standing transmission gratings. The spectrometer combines, high (up to 10,000 lines/mm) and low line density gratings that enable recording of the source spectrum with high resolution and also in a wide bandwidth extending beyond the DUV wavelengths. Compared to a reflective grating configuration, the transmission geometry enables the design to be more compact, and the alignment and calibration to be more straightforward. The components in the spectrometer are controlled by motorized stages that enable adjusting spectral resolution and spectral range without breaking vacuum. We present measurements that were carried out at different types of EUV sources and at various spectral ranges. The measurements provide comprehensive spectral information that is directly available for analysis and optimization of the source conditions.

Presenting Author

Muharrem Bayraktar earned his BSc degree from Bilkent University in 2007, MSc degree from Sabanci University in 2010 and PhD degree from University of Twente in 2010. His MSc research was on digital holography and interference techniques, and applications of these techniques in three-dimensional imaging and metrology. During PhD, his research included development of spectral filters and novel adaptive optical components based on piezoelectric thin films for Extreme Ultraviolet (EUV) wavelengths. He continues his postdoctoral research in University of Twente on developing a broadband spectrometer for characterization of EUV light sources with the valorization grant awarded by the NanoNextNL programme of Netherlands.

S82

Femtosecond Laser Ablation of a Solid Tin Target

M.J. Deuzeman*, †, E. Leerssen*, A. Stodolna*, N. Spook*, ‡, S. Witte*, §, P.C.M. Planken*, ‡, K.S.E. Eikema*, §, W. Ubachs*, §, R. Hoekstra*, †, O.O. Versolato*

** Advanced Research Center for Nanolithography (ARCNL), Science Park 110, 1098 XG Amsterdam, The Netherlands*

† Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

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

‡ Van der Waals-Zeeman Institut, University of Amsterdam, Science Park 904, 1098 XH, Amsterdam, The Netherlands

Laser-produced plasma (LPP) sources generate ionic debris which can damage nearby optic elements. A characterization of this debris and more knowledge about the underlying ionization mechanisms are necessary in order to prevent this damage. We present a study on the femtosecond pulsed laser ablation of a planar, solid tin target. The ablation rate is investigated by measuring the ablation depth, the ablation radius, and the profile of the damage on the target with a high-NA optical microscope. The energy of the ions is measured employing time-of-flight techniques. The ion energy distributions and yield, as well as the ablation rate are characterized for different parameters, such as the laser pulse energy and pulse length. This yields some interesting relationships, which give insight in the processes occurring at the target surface.

Presenting Author

S83

Compact Discharge based EUV Source with High-power and Long Maintenance Interval

Jochen Vieker and Klaus Bergmann

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

In this talk we will present the FS5440 EUV source based on a hollow cathode triggered discharge in xenon. It generates more than 40 W/2□sr in band EUV power at 13.5 nm out of a pinch plasma with a brightness of >12 W/mm²sr. The focus will be on fundamental studies on the interplay between electrode geometry and operating gas flow and pressure, as well as its influence on the EUV power. We found a relative particle count, being the product of an active electrode volume and gas pressure, to be constant for the operation of the source at highest conversion efficiency. With this knowledge and improvements on triggering, it is now possible to adapt the source's settings in order to keep the EUV emission less sensitive to the electrode conditions, thus increasing the effective lifetime. The understanding of gas flow dynamics and their influence on conversion efficiency leads to a new design of the electrode system that also can employ sputter resistant high-temperature compounds near the plasma. Recent progress in increasing the maintenance interval and power scaling to >60 W/2□sr will be presented.

Presenting Author

Jochen Vieker received his Diploma (M.S.) in physics in 2011 from Bielefeld University, for his work on high harmonic generation. Since then he has been scientist in the EUV technology group at the Fraunhofer Institute for Laser Technology. He is manager of the projects related to the FS54 EUV sources. He also is a PhD student at the RWTH Aachen University. Fields of research include fundamental research on gas discharge systems as well as the development of EUV sources with attention towards brightness, output power and long term stability.

S84

Development of a Collective Thomson Scattering System for High-Z Plasmas for Soft X-ray Sources

Yuta Sato, Kentaro Tomita, Toshiaki Eguchi, Syoichi Tsukiyama, Kiichiro Uchino

Interdisciplinary Graduate School of Engineering and Sciences, Kyushu University, 6-1, Kasugakoen, Kasuga, Fukuoka 816-8580, JAPAN

We have developed a collective laser Thomson scattering system using the ion feature for EUV light source plasmas, and revealed spatial profiles of plasma parameters such as electron density (n_e), electron temperature (T_e), and averaged ionic charge (Z)[1)]. However, this system is not sufficient to diagnose plasmas produced for beyond- EUV light and water-window light sources, with which less than 10 nm wavelength emission are required. This is because there is no information of the shape of ion feature due to high number of averaged ionic charge. To solve this issue, we suggested that simultaneous measurement of the ion feature and the electron feature. The n_e and T_e can be measured from the electron feature. Therefore, the electron feature makes up for insufficient information of the ion feature. Before applying a simultaneous measurement system to Beyond-EUV light source plasmas, we will try to diagnose the air break down plasmas and the laser produced carbon plasmas to evaluate the system.

1:Kentaro Tomita et al.:" Development of a collective Thomson scattering system for laser-produced tin plasmas for extreme-ultraviolet light sources", Appl. Phys. Express 8, 126101 (2015).

Presenting Author

Yuta Sato received B.S., M. S., degree in electrical engineering from Kyushu University, Japan, in 2014, 2016, respectively. He is now a doctor course student in Kyushu University, and is working about diagnostics of laser-produced plasmas for EUV, and B-EUV light sources.

S85

Optimization of Extreme Ultraviolet Emission and the Time of Flight Spectra with Dual-pulse Laser Irradiating Tin-droplet Target

Lan Hui [1], Wang Xinbing [2], Zuo Duluo [2], Zheng Guang[1]

[1] School of Physics and information engineering, Jianghan University, Wuhan 430056, China

[2] Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China

The EUV emission and time of flight (TOF) spectra in dual-pulse laser produced plasma (LPP) have been investigated based on tin-droplet target. A series of EUV IRDs and Faraday Cups are employed to detect the EUV emission and ion signals under the condition of coaxial dual-pulse laser that the pre-pulse was Nd: YAG laser and the main pulse was CO_2 laser. The effects of pre-pulsed laser intensity and delay timings between the pre-pulsed and the pumping pulse were investigated to find the optimal pre-plasma conditions before the pumping pulse. The initial optimization of these parameters resulted in 15% increase in EUV conversion efficiency (CE) from the tin LPP. The ion kinetic energies were calculated and comparatively analyzed. The results illustrate that the ion average kinetic energy of dual-pulse LPP were smaller than that of main pulse LPP with independent of the delay time. Furthermore, the ions TOFs in dual-pulse LPP have been fitted by a superimposed Maxwell–Boltzmann distribution and thus obtained the variation plasma temperature and mass-center velocity with delay time in dual-pulse LPP.

Acknowledgement: Research was supported by the Director Fund of WNLO and the National Natural Science Foundation of China under contract No. 61575085.

Presenting Author

Lan Hui is the presenting author for this annual workshop. She is a Ph.D candidate at Huazhong University of Science & Technology, Wuhan, China. She has started her doctorate of optical engineering at Laser and terahertz laboratory in Wuhan National Laboratory for Optoelectronics since 2011. Her main research is laser produced tin plasma EUV source.

S86

Advanced Laser Development for Plasma-based EUV Generation

Tiago Pinto, Randy Meijer, Aneta Stodolna, Stefan Witte, Kjeld Eikema

Advanced Research Center for Nanolithography

The new generation of nanolithography is based on extreme ultraviolet (EUV) radiation technology, where EUV light is produced in a laser produced plasma (LPP). Many complex physical processes underlie the emission of EUV radiation from such a plasma. The goal of our research is to study the efficiency and dynamics of EUV production as a function of the parameters of the LPP driving laser. We will present our progress on the development of an ultrafast parametric amplifier for intense femtosecond pulses, and a high-energy diode-pumped picosecond laser-amplifier. In addition, we present a Nd:YAG based laser at 1064 nm wavelength, which is capable of delivering 250 mJ pulses with 1-1000 ns pulse duration and full control over the temporal pulse shape. These systems independently, and together in pump-probe configurations, are powerful tools in understanding EUV production by LPPs.

Presenting Author

S87

In-line EUV beam Monitoring using Microwaves

F.M.J.H. van de Wetering[1], O.J. Luiten[1], G.J.H. Brussaard[2], V.Y. Banine[1,2] & J. Beckers[1]

[1] Eindhoven University of Technology, Department of Applied Physics, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
[2] ASML The Netherlands B.V., PO Box 324, 5500 AH Veldhoven, The Netherlands

The current paper will describe an alternative method of accurate dosimetry of extreme ultraviolet (EUV) and X-ray radiation of such sources as free-electron lasers or tight bundles produced by other EUV radiation sources. In these devices, the high-energy photons ionize the (residual) background gas, effectively generating a rarefied plasma. The EUV beam is non-intrusively characterized (power, position and cross-sectional profile) by studying the plasma, in particular the created free electrons, using a microwave cavity placed around the EUV beam. Free electrons locally change the permittivity of a cavity at resonance, which results in a shift of the resonance frequency compared to an empty one. The electric field pattern of the excited resonant mode determines the sensitivity of the method to free electrons and thus to what extent the frequency changes. This means that spatial information about the created electron cloud (position and cross-sectional profile) can be obtained by combining several resonant modes. For 100 eV photons in argon at 10^{-7} mbar, a fluence between roughly 1 and 10^{7} J/m^2 can be measured with a time resolution down to 10 ns. We present first results on the development of such a multi-mode cavity and its application to well-known laboratory plasma sources.

Presenting Author

EUV

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