2017 Source Workshop

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Dublin ▪ Ireland

Workshop Abstracts

EUV Litho, Inc.

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2017 Source Workshop

Workshop Co-Organizers

Welcome

Dear Colleagues;

I am delighted to invite you to the 2017 Source workshop in Dublin, Ireland.

Source workshop, now in its 8th year, is the largest annual gathering of EUV and XUV source experts and this meeting continues to grow! This year we are including new topics of broad-band EUV sources and lasers, as these topics have become important for continued success of EUV Lithography. As always workshop will provide a forum for researchers in the EUV and soft X-ray areas to present their work and discuss potential applications of their technology. The workshop proceedings will be published online and made available to all.

This year, the EUV Source Workshop is organized by University College Dublin (UCD) and EUV Litho, Inc. This workshop has been made possible by the support of workshop sponsors, technical working group (TWG), workshop support staff, session chairs and presenters. I would like to thank them for their contributions and making this workshop a success. I look forward to your participation in the workshop.

Best Regards

Vivek Bakshi
Organizing Chair, 2017 Source Workshop

Source Technical Working Group (TWG)

Reza Abhari (ETH Zurich)
Jinho Ahn (Hanyang University)
Peter Anastasi (Silson)
Sasa Bajt (DESY)
Igor Fomenkov (ASML)
Klaus Bergmann (ILT-Fraunhofer)
Davide Bleiner (University of Bern)
John Costello (DCU)
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Vivek Bakshi (EUV Litho, Inc.) - Organizing Chair
Padraig Dunne (UCD)– Co-Chair

ABSTRACTS

S1

Imaging Biological Cells using Soft X-ray Tomography

(Keynote Presentation)

Carolyn Larabell

University of California San Francisco School of Medicine and Lawrence Berkeley National Laboratory

Until recently, transmission electron microscopy (TEM) was the only technique available for obtaining high-resolution images of cellular structures. Since intact cells are transparent, comprised of about 70% water, and too large to be penetrated by an electron beam (microorganisms are several microns in diameter; most mammalian cells are at least 10 microns diameter), extensive specimen preparation techniques are required. Cells must be dehydrated using a slow, gradual incubation in increasing concentrations of solvents; this leads to collapse of delicate structures as well as loss of soluble cell components. Cells also must be stained with heavy metals to generate sufficient contrast. Finally, cells must be embedded in plastic to facilitate collection of ultra-thin (≤ 100 nm) sections capable of electron beam penetration. The extensive processing required to image just a small portion of a cell is destructive and time-consuming, taking from 3-5 days. Soft x-ray tomography (SXT) is an excellent alternative for imaging cell structures in the native state, avoiding all of the damaging processing required for TEM. Cells are simply rapidly frozen, placed in a goniometer, and imaged from multiple angles. Three-dimensional images of an entire cell can now be imaged in just five minutes. At the National Center for X-ray Tomography in Berkeley California, we are working with a large number of biologists from around the world to image a variety of different cell types. I will present examples of many of these projects that reflect the broad applications of SXT.

Presenting Author

Carolyn Larabell is Professor and Vice-Chair in the Department of Anatomy at the University of California San Francisco School of Medicine, with a joint appointment as Advanced Light Source Professor at Lawrence Berkeley National Laboratory. She is also the Founding Director of the National Center for X-ray Tomography (NCXT), a NIGMS-NIH Biomedical Technology Research Resource, to develop soft x-ray microscopy for imaging biological cells. Dr. Larabell received her Ph.D. from Arizona State University and did postdoctoral training at Stanford University and the University of California at Davis.

S2

EUV Source for High Volume Manufacturing: Performance at 250 watt, and Key Technologies for Power Scaling

(Keynote Presentation)

Igor Fomenkov

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This paper discusses the latest improvements in the performance of an EUV source for semiconductor lithography including power scaling and availability. EUV source performance has met the 250W targeted power level, significantly improved in dose stability, and increased in availability. The improvement in performance has been achieved due to implementation of the latest developments in EUV source subsystems including the tin droplet generator, CO_2 laser and control system.

This paper describes the development of laser-produced-plasma (LPP) extreme-ultraviolet (EUV) sources for advanced lithography applications in high volume manufacturing. We discuss the most recent results from high power testing on our development systems, and describe the solutions and technical challenges related to the implementation of these technologies. Subsystem performance will be shown including Master Oscilator Power Amplifier (MOPA) Pre-pulse operation with high Conversion Efficiency (CE) and dose control with low overhead and high die yield. We describe the most effective optimized modes of operation to control the plasma dynamics at high power and with the necessary collector protection. This presentation reviews the experimental results obtained on NXE:3400B sources with a focus on the topics most critical for a 250W HVM LPP source.

Presenting Author

Igor Fomenkov is an ASML Fellow in Technology Development Group in San Diego, California. After completing a Ph.D. in Physics and Mathematics at Moscow Institute of Physics and Technology (MPTI) in 1986, he joined General Physics Institute as a senior scientist, where he worked in the field of interaction of high intensity laser radiation with matter and diagnostics of laser produced plasma. He joined Cymer in 1992 and worked on the development of high power, high reliability KrF and ArF Excimer lasers for DUV (at 248nm and 193nm) microlithography. Since 1997 he has been conducting research and development of sources for Extreme Ultraviolet Lithography at 13.5nm. He was appointed Cymer Fellow in 2003 and ASML Fellow in 2014. He has authored over 50 technical papers and holds over 100 patents in the areas of DUV and EUV light sources.

S11

Atomic Data of Low-charged Sn ions for Lithography Applications

J. Colgan, D. P. Kilcrease, J. Abdallah, Jr., M. E. Sherrill, C. J. Fontes, and P. Hakel

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The intense emission of tin plasma in the 13.5 nm wavelength band has long been recognized for its potential as a powerful EUV source with important lithography applications. To this end, significant work has been carried out in efforts to both predict the emission from the atomic ions of relevance, and to perform numerical predictive simulations of EUV sources.

The efforts to predict the plasma properties of Sn that produce these intense emission features are complicated by the complex atomic structure of the Sn ions in question (normally from around 5 times ionized to 20 times ionized). We have begun preliminary investigations into the atomic structure and opacity of Sn at low temperatures (< 50 eV), where these ions dominate the absorption features. The opacity is closely related to the emissivity when thermodynamic equilibrium holds, and is also important for understanding the self-absorption of the plasma. Recently, we have explored the accuracy of some approximations used in atomic structure models for the relevant ion stages of Sn [1]. We find that the use of intermediate-coupling, as compared to full configuration-interaction, is not adequate to obtain accurate line positions of the important bound-bound transitions in Sn. One requires full configuration-interaction to properly describe the strong mixing between the various n=4 sub-shells that give rise to the Δn=0 transitions that dominate the opacity spectrum at low temperatures.

Since calculations that include full configuration-interaction for large numbers of configurations quickly become computationally prohibitive, we have explored hybrid calculations, in which full configuration-interaction is retained for the most important transitions, while intermediate-coupling is employed for all other transitions [1]. Our calculations are performed using the Los Alamos suite of atomic physics codes (for an overview, see [2]). After extensive exploration of the atomic structure properties, local-thermodynamic-equilibrium (LTE) opacities are generated using the ATOMIC code [3,4,5] at selected temperatures and densities. Preliminary results indicate that our models find quite good agreement with transmission measurements from laser-produced Sn plasmas [6].

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Presenting Author

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

S12

EUV Spectra of Highly Charged-ions Observed with a Compact Electron Beam Ion Trap

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We present EUV spectra of highly charged heavy ions relevant to developing LPP-EUV sources, such as Mo, Gd, and Tb, obtained with an electron beam ion trap (EBIT). An EBIT produces highly charged ions through successive ionization of trapped ions by a quasi-monoenergetic electron beam; thus it can provide selected charge state ions in the trap by tuning the electron beam energy. Simple spectra obtained from ions with a sharp charge distribution are useful to disentangling LPP spectra and also to identify previously unreported lines.

We have been using a compact EBIT, called CoBIT [1], which has a suitable electron beam energy range for producing 4d- and 4f-ions. A grazing incidence flat field grating spectrometer specially designed for CoBIT has been used for observing EUV emission from the ions trapped in CoBIT. Experimental spectra are compared with LPP spectra and also with theoretical spectra calculated with a collisional radiative model.

[1] N. Nakamura et al., Rev. Sci. Instrum. 79 (2008) 063104

Presenting Author

Nobuyuki Nakamura is an associate professor at Institute for Laser Science, the University of Electron-Communications (UEC Tokyo, Japan), and the group leader of the Tokyo EBIT project. He received his Ph.D. from UEC in 1996, and has been working in UEC since 2003 after working as a postdoctoral researcher at JST and RIKEN. His main research interest is relativistic effects on the spectra and dynamics of highly charged heavy ions. He also contributes to providing atomic data of highly charged ions relevant to hot plasma physics.

S13

Fundamental Studies of Sn^{7+}-Sn^{14+} Ions with Applications for Laser Produced Plasma Sources

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We experimentally re-evaluate the fine structure of Sn^{7+}-Sn^{14+} ions. These specific ions are used to generate extreme ultraviolet (EUV) light at 13.5-nm wavelength in laser-produced-plasma (LPP) sources. The EUV light is generated by thousands of transitions that form so-called unresolved transition arrays (UTAs). Understanding the complex electronic structures of the involved ions remains challenging for both theory and experiment due to their open 4*d*-shells. In this work, charge-state-resolved optical and extreme ultraviolet spectra of Sn^{7+}-Sn^{14+} ions were obtained using an electron beam ion trap. Semi empirical spectral fits carried out with the orthogonal parameters technique and COWAN code calculations lead to identifications of magnetic-dipole transitions and the determination of energy ground-configuration levels, questioning some earlier EUV-line assignments. Available Ritz combinations further strengthen our analysis. Comparison with configuration-interaction many-body perturbation theory calculations and Fock space coupled cluster calculations confirm the predictive power of these state-of-the-art *ab initio* methods. The present measurements and identifications provide immediate input for optical plasma-diagnostic tools and advance our understanding of the formation of the Sn ion UTAs.

Presenting Author

Hendrik Bekker is a postdoc at the Max Planck institute for nuclear physics in Heidelberg, Germany. Before finishing his PhD in Heidelberg, he earned his MSc degree in physics at the university of Groningen.
Currently, he works in the group of José R. Crespo López-Urrutia that specializes in the physics of highly charged ions (HCI).

S14

Tin Ion Spectroscopy on Plasma Sources of EUV Light

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We present our progress on tin ion spectroscopy using line spectra obtained from the Sn LPP EUV source installed at ARCNL – Amsterdam. In the EUV spectral regime we have achieved identification of the transition arrays contributing to the out-of-band spectral features at wavelengths between 8 and 13 nm. These out-of-band fingerprints of individual contributions of various charge states of tin might aid the assessment of the different ionic charge states contributing to the in-band radiation at 13.5 nm.

In the optical spectral regime, by means of a masking technique we have obtained the individual spectra of SnIII, SnIV, and SnV. As an example I will discuss the SnIV for which we observed and identified some 50 lines, of which the majority hadn't been identified before. This line identification unravels and clarifies details of the electronic structure of SnIV, e.g. an over 300 cm^{-1} shift of the ionization potential and anomalous fine structure splitting induced by configuration interaction.

Presenting Author

S21

Atomic and Radiative Processes in High-Z Plasmas and their Applications in EUV Lithography and "Water Window" Imaging

Bowen Li[1], Takeshi Higashiguchi[2], Takamitsu Otsuka[2,5], Hayato Ohashi[3], Chihiro Suzuki[4], Emma Sokell[5], Padraig Dunne[5], Yang li[1], Xiaokai Xu[1], Ximeng Chen[1], and Gerry O'Sullivan[5]

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The behavior of the highly-charged ion (HCI) in heavy ion element plasmas is currently of major interest and has been motivated by their application in a number of high profile areas of science and technology, such as source for EUV lithography as well as laboratory plasma light sources. Systematic calculations for UTA positions were performed for elements with atomic number Z = 49–92, with the help of both laser produced plasmas (LPPs) and Large Helical Device (LHD) experimental measured spectra it was found that the peak such UTAs in optically thin plasmas in the extreme ultraviolet region follows a quasi-Moseley's law. Considerable effort has been made to obtain reliable atomic data, including emission lines and various rate coefficients, to enable identification of reference lines for plasma diagnostics, to reliably estimate concentration, ionization balance and to find optimum plasma conditions. From spectral analysis of high-Z plasmas, we demonstrated a potential "water window" source based on the use of a laser produced plasma, coupled with multilayer mirror optics.

Presenting Author

Bowen Li an associate professor in the school of nuclear science and technology, Lanzhou University. He received his PhD from UCD in 2013. His research focuses on atomic structure and radiative process in plasma and laser-plasma interaction.

S22

Towards High-Fidelity Simulations of EUV Production from Laser-Produced Plasma

Howard Scott

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Numerical simulations of laser-produced plasmas are routinely employed as valuable tools in a wide variety of technical endeavors. Using simulations can deepen our understanding of physical systems by providing both a view of details unavailable from experimental diagnostics and the opportunity to improve our understanding and intuition by numerical experimentation. Exercising this opportunity requires the availability of high-fidelity, predictive numerical simulations based on accurate models of the underlying physical phenomena.

The general microphysics of EUV production from laser-produced plasma is relatively well understood and models built on this understanding have guided efforts to design more efficient sources. However, the complex interactions of the physical processes are extremely difficult, if not intractable, to model in detail, so existing numerical simulations depend on a variety of approximations. Providing high-fidelity simulations that can reproduce, and eventually predict, EUV production over a range of physical conditions and scenarios requires improving upon these approximations.

We discuss numerical models of critical microphysics processes for EUV generation, emphasizing underlying approximations and corresponding restrictions. In particular, we focus on issues arising from the treatment of atomic kinetics in the radiation-hydrodynamics simulation of the radiating plasma.

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

Presenting Author

Howard Scott is a staff physicist at Lawrence Livermore National Laboratory where he has been developing simulation codes since 1986. He holds a PhD in astrophysics and has worked in the areas of inertial confinement fusion, magnetic fusion energy, X-ray lasers, nuclear weapons, and even some astrophysics. His particular research interests are radiation transport, non-LTE physics, plasma spectroscopy and large-scale simulations.

S23

Soft X-ray Spectroscopy of Dy, Er and Tm Ions Excited in Laser-Produced Plasmas

John Sheil[1], Takeshi Higashiguchi[2], Domagoj Kos[1], Takanori Miyazaki[1,2], Fergal O'Reilly[1], Gerry O'Sullivan[1], Paul Sheridan[1], Emma Sokell[1], Chihiro Suzuki[3] and Deirdre Kilbane[1]

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Research involving the spectroscopy of highly charged lanthanide ions has gained momentum in recent years. The main driving force behind this resurgence owes in large part to the potential application of these ions in many high-profile fields, such as fusion, plasma diagnostics, soft x-ray lasers, next-generation lithography and water window source development [1 – 5]. The availability of high quality atomic data is crucial to the development of these fields. However, to date, very few spectroscopic studies of these ions have been undertaken. Furthermore, the complex structure of open 4f subshell ions makes accurate calculations of these spectra notoriously difficult. The aim of this study is to bridge the gap in our current understanding of soft x-ray radiation emitted from open 4d and 4f subshell heavy lanthanide ions.

Emission spectra of dysprosium, erbium and thulium ions created in laser-produced plasmas were recorded with a flat-field grazing incidence spectrometer in the wavelength range 2.5 – 8 nm. The ions were produced using a Nd:YAG laser of 7 ns pulse duration and the spectra were recorded at various power densities. The experimental spectra were interpreted with the aid of the Cowan suite of atomic structure codes [6] and the flexible atomic code (FAC) [7]. Above 5.5 nm the spectra are dominated by overlapping Δn = 0, n = 4 – n = 4 unresolved transition arrays (UTAs) from adjacent ion stages. The origin of an interesting feature located on the long wavelength side of these UTAs is examined. Following a detailed analysis, we have tentatively identified these features as 4d2 3F2 – 4d4f 3G3 transitions in Sr – like ions. However, further experimental and theoretical validation is needed in order to clarify these assignments. Below 6 nm, Δn = 1, n = 4 – n = 5 transitions originating from ions with open 4d and 4f subshells give rise to a series of interesting overlapping spectral features. In addition, it was found that satellite transitions of the form 4fn-15s – 4fn-25s5g and 4dm-15s – 4dm-25s5p make a significant contribution to this region of the spectrum.

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Presenting Author

S24

Modeling of Particle Debris from the Target of Laser Produced Plasma EUV Sources

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A hydrodynamics model of ablation of the laser irradiated target is presented. The particle debris emitted from the target is of the interest because of the contamination of the collector optics. Dynamics of the particles are also interested to produce the plasma with an appropriate density distribution using the double pulse technique. We develop a two dimensional Lagrangian hydrodynamics code with algorithms of reorganization of mesh and the model of liquid-to-gas transition. We investigate the emission of the particle debris by rapid heating of the target material as well as by a shock wave caused by the irradiation of intense short laser pulse.

Presenting Author

Akira Sasaki received the Dr. Eng. degree in energy science from Tokyo Institute of Technology, Tokyo, Japan in 1991. He joined Japan Atomic Energy Agency in 1996; the organization has changed in 2016 to Kansai Photon Science Institute, National Institutes for Quantum and Radiological Science and Technology. He has been studying theoretical modeling and simulation of the atomic processes and radiation hydrodynamics of EUV source for lithographic applications since 2002.

S25

Measurements and Numerical Simulations of Sn ion Stopping in Low-pressure H_2 Atmosphere

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We report on the studies of Sn ion stopping in H_2 gas. In the experiments, laser produced plasma was used as a source of Sn ions with energies ~0.1-5 keV. Pulsed CO_2 laser radiation was used to generate plasma by irritation of a bulk tin target. Time of flight tube and electrostatic ion energy analyzer were used to measure energy the ion stopping power of H_2 gas. The experiments were complemented with numerical simulations utilizing our home-made particle-in-cell plasma code coupled with Monte Carlo particle tracer. The numerical simulations were used to extract the ion stopping cross-sections.

Presenting Author

Viacheslav Medvedev is project coordinator at RnD-ISAN/ISTEQ. He received his PhD from the University of Twente, XUV Industrial focus group. Viacheslav has research experience in the field of sources and optics for short-wavelength radiation, including soft X-rays and EUV.

S31

High Average Power and High Energy Ultrafast Thin-Disk Amplifiers

Thomas Metzger

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Industrial thin-disk laser technology developed by TRUMPF Laser is routinely used for generating multi-millijoule pulses with durations of < 1.5 ps at kilohertz repetition rates. Recently record values of 220 mJ were demonstrated at 1 kHz [1] and >1 kW average power with up to 200mJ [2,3]. Further increase of the pulse peak power can be obtained via spectral shaping resulting in pulse durations below 700 fs. Thanks to their excellent beam quality and hence focusability, intensities of $<10^{16}$ W/cm² are easily achievable. We believe that these ultrafast thin-disk amplifiers are now mature for the semiconductor industry as pre-pulse lasers or towards X-ray generation applied to waver metrology. The talk will give an overview of the current status and development at TRUMPF Scientific Lasers regarding ultrafast thin-disk amplifiers.

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[3] T. Nubbemeyer, et. al.: "1 kW, 200 mJ picosecond thin-disk laser system," Opt. Lett. **42**, 1381 (2017).

Presenting Author

Thomas Metzger studied mechanical engineering at the Technical University in Stuttgart and received his Diploma in 2002. After his degree he worked in 2003 as an intern at Spectra-Physics. During his PhD and as Postdoc in the research group of Prof. Ferenc Krausz at the Technical University in Vienna and the Max-Planck Institute of Quantum Optics in Garching, he developed ultrafast thin-disk amplifiers in close collaboration with TRUMPF Laser. Since 2012 Thomas Metzger is CTO at TRUMPF Scientific Lasers GmbH + Co. KG.

S32

High-harmonic Generation for Metrology Applications

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High-harmonic generation (HHG) of infrared femtosecond driving pulses allows beam sources in the extreme ultraviolet (XUV) with diffraction-limited beam quality and large temporal coherence, enabling attosecond pulses and, at high repetition rate, XUV frequency combs. In order to exploit the high average power (several 100 W) of ytterbium-doped laser systems with rather long pulses (several 100 fs) for HHG, we developed an efficient nonlinear pulse compression scheme suitable for previously inaccessible pulse energy range around 10 µJ. We developed schemes for efficient geometrical output coupling of the XUV radiation generated inside an enhancement resonator. We report on the status of our HHG setups for attosecond pulses for photo-electron spectroscopy and for an XUV frequency comb for precision spectroscopy of the 1s-2s transition in helium+ ions.

Presenting Author

Johannes Weitenberg was born in Rhede, Germany in 1981. He studied physics at RWTH Aachen University, Germany and received the Diploma degree in 2007. From 2008 to 2015 he has been working at the Chair for Laser Technology of RWTH Aachen University and since then at Fraunhofer Institute for Laser Technology, Aachen. Since 2015 he has been working at the Max-Planck Institute of Quantum Optics, Garching, Germany. His current research interests include development of solid-state lasers, high-harmonic generation, enhancement resonators, nonlinear pulse compression and frequency-comb-spectroscopy.

S33

Development of kW-level picosecond thin-disk pre-pulse laser for high-power EUV sources

J. Mužík, M. Smrž, M. Chyla, O. Novák, A. Endo, T. Mocek

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High-average-power picosecond solid-state lasers became an important part of the extreme ultraviolet (EUV) lithography technology using laser-produced plasma (LPP) and its power scaling efforts. They enable to increase the conversion efficiency from laser to 13.5-nm EUV emission multiple times by conditioning the droplet target with a picosecond pre-pulse into a uniform mist form before it is hit by the main CO_2 laser pulse. This talk will present the development status of a kW-level, high-repetition-rate picosecond laser system PERLA C being developed at the HiLASE Centre in the Czech Republic and with parameters relevant for LPP-EUV lithography.

The PERLA C laser system is based on Yb:YAG thin disk gain medium and uses the CPA (chirped pulse amplification) technique. The current work focuses on finalizing the main regenerative amplifier and pulse compression with a chirped volume Bragg grating. The laser system is now capable to produce 9-mJ pulses at 50 kHz repetition rate (450 W average power) with possibility to further increase the repetition rate, prospectively to 1 MHz. Further upgrade plans to 1 kW average power and pulse shaping options for LPP will be also discussed.

Presenting Author

Jiří Mužík is a Junior Researcher at the HiLASE Centre in Dolní Břežany, Czech Republic, where he is involved in development of high-average-power picosecond thin-disk laser systems. He is currently working towards the PhD. degree in Physical Engineering at the Czech Technical University in Prague. His research interests include high-power thin-disk lasers and mid-IR solid-state lasers.

S34

Modelling of Hybrid Pumping of Nitrogen Recombination Laser

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High current capillary pinching discharge was studied as a method for recombination pumping at Balmer α transition of hydrogen like nitrogen, corresponding to the laser wavelength of 13.4 nm. It was stated that the principal requirements for this pumping are plasma electron heating up to 120 eV during the pinch collapse and quick electron cooling during the pinch expansion phase. Required large electrical currents passing through the capillary cause a strong ablation of all wall material and thus reduction of efficient nitrogen plasma heating and slowing down plasma cooling during the pinch expansion phase [1,2]. We report here computer modelling of hybrid nitrogen recombination laser pumping by capillary discharge and by nanosecond optical laser pulse as a certain analogy to the collision hybrid excitation [3]. The modelling has been performed for the alumina capillary plasma fed by current pulses of 30-60 kA and 1-2 J nanosecond Nd:YAG laser pulses injected at the moment when the radially concave electron density profile is present. The results predict creating an active laser medium with reasonable gain.

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Presenting Author

S41

High Power LPP-EUV Source with Long Collector Mirror Lifetime for High Volume Semiconductor Manufacturing

Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Krzysztof M Nowak, Yasufumi Kawasuji, Hiroshi Tanaka, Yukio Watanabe, Tsukasa Hori, Takeshi Kodama, Yutaka Shiraishi, Tatsuya Yanagida, Georg Soumagne, Tsuyoshi Yamada, Taku Yamazaki and Takashi Saitou

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We have been developing CO_2-Sn-LPP EUV light source which is the most promising solution as the 13.5nm high power light source for HVM EUVL. Unique and original technologies such as; combination of pulsed CO_2 laser and Sn droplets, dual wavelength laser pulses shooting and mitigation with magnetic field have been developed in Gigaphoton Inc.. We have developed first practical source for HVM; "GL200E" [1)] in 2014. We have proved high average power CO2 laser more than 20kW at output power cooperate with Mitsubishi electric cooperation[2)]. Pilot#1 is up running and its demonstrates HVM capability; EUV power recorded at111W average (117W in burst stabilized, 95% duty) with 5% conversion efficiency for 22hours operation in October 2016[3)]. Recently we have demonstrated, EUV power recorded at113W in burst stabilized (85W in average, 75% duty), with 5% conversion efficiency during 143hours operation. Also the Pilot#1 system recorded 64% availability and idle time was 25%. Availability is potentially achievable at 89% (2weeks average), also superior magnetic mitigation has demonstrated promising mirror degradation rate (= 0.5%/Gp) above 100W level operation with dummy mirror test.[4)].

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3) Hakaru Mizoguchi et al., Performance of 250W High Power HVM LPP-EUV Source, Proc. SPIE 10143, Extreme Ultraviolet (EUV) Lithography VIII (2017)
4) Hakaru Mizoguchi, et al, High Power HVM LPP-EUV Source with Long Collector Mirror Lifetime, EUVL Workshop 2017, (Berkley, 12-15, June, 2017)

Presenting Author

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

S42

Two-dimensional Electron density and Temperature Profiles of EUV Light Sources with 4.0% CE

Kentaro Tomita[1], Yuta Sato[1], Syoichi Tsukiyama[1], Raimu Fukada[1], Fumitaka Ito[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]

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[2] *Gigaphoton Inc., 400 Yokokurashinden Oyama,Tochigi, 323-8558, JAPAN*

Detailed collective Thomson scattering (CTS) measurements have clarified two-dimensional structures of electron density (n_e) and electron temperature (T_e) of laser produced Sn plasmas for EUV lithography light sources[1)]. We compared three types of plasmas, whose conversion efficiencies (CE) were 2.8, 3.1, and 4.0%. For these plasmas, typcila ranges of n_e and T_e were 10^{24}-10^{25} m^{-3}, and 20-40 eV, respectively. To confirm validities of CTS measurements, we compared pin-hole EUV emision profiles, which showed line-integrated 2D-profiles of in-band EUV images, with EUV emissivity profiles, which was calculated by the measured n_e and T_e and atomic model (Hullac code)[2)]. Resutls of thisn comarison strongly indecated the reliablility of the CTS measuremments. Moreover, the CTS results showed that for the highest CE condition (4.0%), the n_e profiles formed a hollow-like structure. We believe that this hollow-like structure is necessary to realize the higher CE.

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Presenting Author

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

S43

Short-wavelength Out-of-band EUV emission from Sn Laser-produced Plasma

Francesco Torretti

EUV Plasma Processes group, Advanced Research Center for Nanolithography (ARCNL), Science Park 110, 1098XG Amsterdam

We present the result of spectroscopic measurements in the EUV regime obtained for micrometer sized Sn droplets irradiated by a high-intensity Nd:YAG laser in an industrially relevant setting for nanolithographic applications. We focus on the high-energy, short-wavelength features between 7 nm and 12 nm. Using atomic structure calculations and local thermodynamic equilibrium arguments, we show that these emissions can be explained by high-energy configurations within the same ions responsible for 13.5 nm photons in EUV sources. Our results can be used to reliably identify the charge state distribution in this Sn laser-produced plasma, thus providing valuable diagnostic information.

Presenting Author

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

S44

Expansion Dynamics after Laser-induced Cavitation in Liquid Tin Microdroplets

D. Kurilovich[1,2], T. Pinto[1,2], R. Schupp[1], F. Torretti[1,2], J. Scheers[1,2], A. Stodolna[1,2], W. Ubachs[1,2], R. Hoekstra[1,3], S. Witte[1], O.O. Versolato[1]

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[3]*Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*

We present a detailed analysis of the expansion dynamics of liquid tin microdroplets after picosecond-laser-induced cavitation, combining high-quality stroboscopic shadowgraphy with an intuitive fluid dynamic model. Excellent agreement with our model is obtained regarding the hydrodynamic scalability of the data with expansion velocity as well as for two different droplet sizes. Furthermore, we provide late-time target mass distributions and demonstrate that different such distributions can be obtained deterministically within the here presented formalism. Our detailed studies are performed under industrially directly relevant conditions as found in next- generation nanolithography machines and we provide a possibly useful phase diagram for different operation regimes for target shaping.

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 EUV light sources based on laser-produced tin plasma.

S45

Vapor shielding of tin under intense plasma bombardment

T.W. Morgan, G.G. van Eden, D.U.B. Aussems, V. Kvon, M.A. van den Berg, K. Bystrov, M.C.M. van de Sanden

DIFFER—Dutch Institute for Fundamental Energy Research, De Zaale 20, 5612 AJ Eindhoven, The Netherlands

Strong heating and plasma bombardment occurs during the ablation and vaporization of tin droplets in EUV sources and in the interaction of exhaust plasma with advanced wall materials for future nuclear fusion power plants. These reactors will generate a large heat and particle exhaust onto a relatively small region of the wall. A promising wall material for this exhaust region is a porous structure impregnated with liquid tin, due to the potential for high heat exhaust capability while eliminating erosion as a lifetime concern by continual replenishment of lost liquid metal. DIFFER's high-flux linear plasma device Pilot-PSI was used to generate plasma conditions similar to those expected in the exhaust region of fusion power plants and used to study the power handling capabilities of such a surface. Under such high heat loads significant tin evaporation occurs. When the evaporative flux becomes comparable to the incoming plasma flux strong interaction between the plasma and the vapor cloud occurs, driving increased radiation, mass loss and recombination processes as the plasma is cooled. This results in a surface-temperature locking phenomena which is found to be oscillatory in nature. This talk will explore this phenomenon and how it also relates to EUV source conditions.

Presenting Author

Thomas Morgan (1984) is the group leader of the Plasma Material Interactions group at the Dutch Institute for Fundamental Energy Research. He received his PhD from the University of York for his work at the MAST tokamak developing a novel charge-exchange diagnostic to measure ion temperatures and velocities. Since then he has been based at DIFFER, first as a postdoc, then EFDA Fellow, project leader and finally group leader. He has published more than seventy peer reviewed journal articles and since 2014 has been the daily supervisor of 8 PhD students. He is scientific coordinator for the Magnum-PSI and Pilot-PSI linear plasma devices at DIFFER and is one of Europe's leading experts on liquid metal interaction with plasma in the context of nuclear fusion research.

S46

ARCNL "Source" projects update

Oscar Versolato

ARCNL

The Advanced Research Center for Nanolithography (ARCNL) is a public-private partnership between the Netherlands Organisation for Scientific Research NWO, the two universities in Amsterdam (UvA and VU), and the company ASML. ARCNL focuses on the fundamental physics behind current and future technologies for application in nanolithography, in particular for the semiconductor industry. I will give an update on the source-related research of the institute, ranging from physics aspects of Nd:YAG laser-driven plasma sources of extreme ultraviolet (EUV) radiation to high-harmonic generation (HHG), a process that enables the production of fully coherent pulses of EUV and soft X-ray radiation using compact high-intensity lasers.

Presenting Author

Oscar Versolato is tenure-track group leader of the EUV Plasma Processes group at the Advanced Research Center for Nanolithography (ARCNL) in Amsterdam. After his promotion at the University of Groningen on laser spectroscopy of radioactive, trapped ions, he worked as a postdoc at the Max Planck Institute for Nuclear Physics in Heidelberg in collaboration with Aarhus University and the PTB in Braunschweig on the topic of highly charged ions. His current research is on the physics of plasma sources of extreme ultraviolet light. Recently, he was awarded a VIDI grant from the Netherlands Organisation for Scientific Research.

S47

Development of a collective Thomson scattering system for laser-produced high-Z plasmas for soft X-ray light sources

Yuta Sato[1], Syoichi Tsukiyama[1], Raimu Fukada[1], Kentaro Tomita[1], Kiichiro Uchino[1]

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We have developed a collective laser Thomson scattering system, which has been adapted to detect the ion feature spectra from 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], [2] 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 on the shape of ion feature due to a high number of averaged ionic charge. To solve this problem, we have been developing a new collective Thomson scattering system, which can detect both the ion feature and the electron feature, simultaneously. Using this system, n_e and T_e can be fixed by the electron feature. Then, Z can be determined from the ion feature even when Z is larger than 15, which is predicted for the beyond- EUV light and water-window light sources. As a first step, we tried to diagnose the helium break down plasmas to test a theory of Thomson scattering. As a result, our new system achieved to obtain same parameters from ion feature and electron feature. Now, we are trying to diagnose the laser produced tin plasmas to evaluate the system.

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Presenting Author

Yuta Sato is a Ph. D. student at Kyushu Univ. He 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 soft X-ray light sources.

S48

Ion Stage Velocity Evolution in CO_2-generated Laser Plasma Plumes

Frank McQuillan, Emma Sokell & Padraig Dunne.
UCD School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

This poster presents the evolution of the velocities achieved by individual ion stages within a plasma plume created by the impact of a CO_2 laser upon a Sn Planar target under vacuum. Ion stage identities and velocities are disaggregated from experimentally derived data and are compared with a similar analysis of ion stage velocity evolution derived from the output of a CRETIN (Scott, 1994) simulation of the same experimental setups. The study includes a review of previous third-party experiments which used similar ion collectors and ESAs (Láska et al., 2008). Local experiments include the use of simple, negatively and positively biased, Langmuir-type ion collector probes and an ion spectrometer based on an energy selective analyser (ESA).

Findings indicate that the wave-train behaviour of the CO_2 laser pulse may modulate the evolution of ion and electron fronts in the plasma plume. Evidence is found that ion stages evolve over space and time in distinct groups, with velocities being driven by both columbic explosion and ambipolar diffusion (Farid et al., 2013).The purpose of the comparison of the CRETIN simulation with the experimental data is to benchmark CRETIN's capabilities against actual experiment (Scott, 2001) .

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Presenting Author

S51

Characterization of Laser-assisted and laser-driven EUV sources for Metrology Applications

Yusuke Teramoto[1], Bárbara Santos[1], Guido Mertens[1], Margarete Kops[1], Ralf Kops[1], Alexander von Wezyk[2], Klaus Bergmann[2], Hironobu Yabuta[3], Akihisa Nagano[3], Takahiro Shirai[3], Yoshihiko Sato[3], Kunihiko Kasama[3]

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The Laser-assisted discharge-produced (LDP) plasma EUV source is being developed as a light source for actinic mask inspection. Although EUV radiation is done by electrical discharge, since the focused laser irradiation is used to ignite the discharge, the LDP plasma has a unique feature of high brightness and high power. LDP source is being used in the beam line application of which rated power is 70 W/2☐sr (after debris filter) and maximum frequency is 10 kHz. The LDP source can be used in an actinic mask inspection tool as well. The stable operation for 5 days was demonstrated at 100 W/mm^2/sr level. And the scalability to 200 W/mm^2/sr level was confirmed. The laser-driven source is being researched aiming at the compact high-brightness source. Currently, Sn is used as a fuel (target) material and the laser irradiation intensity is adjusted to emit radiation at 13.5 nm. The brightness of 75 W/mm^2/sr was measured at 15 kHz operation so far. Both sources were characterized in terms of power, brightness, stability and debris emission.

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 of Xe- and Sn-fueled discharge EUV sources. In 2008, he moved to Aachen, Germany to participate the co-development program between Ushio, XTREME, Philips and Fraunhofer ILT. He engaged in source development for NXE3100, especially in power scaling. Now he is working for BLV Licht- und Vakuumtechnik GmbH, an Ushio group company. He is currently the leader of R&D Unit 1 of EUV Business Project managed by Ushio Inc. and working on EUV and X-Ray metrology sources research and development.

S52

Laser Induced Shockwave Droplet Breakup Dynamics

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CFD simulations are constructed of a Sn droplet impacted by the ablation pressure wave of a pulsed Nd:YAG laser. These simulations were performed in Fluent using the multiphase Volume of Fluid with the coupled level set model, explicit formulation, the geo-reconstruct scheme, and adaptive meshing. The solver was transient and pressure based. The minimum cell size was set to 1.2% of the droplet diameter. The droplet was initialized as a sphere of liquid Sn. The subsequent pressure and velocity distribution from the laser ablation induced shockwave was calculated analytically and set as the initial condition for the droplet. The simulation results were compared against experimental results of the same boundary conditions. The laser pulse irradiance is varied across several cases. The cases were run until the droplet fragmentation ceased. Final fragment size distributions and mass flux distributions are compared for the cases. It was found that the mass averaged fragment sizes of the shocked droplet vary proportionately to $We^{-1/4}$. The debris mass flux distribution is plotted as a function of angle relative to the laser center axis.

Presenting Author

Duane Hudgins is a PhD student at the Applied Laser Plasma Science (ALPS) facility in the Laboratory for Energy Conversion, ETH Zurich since 2013. He completed is MS in the mechanical engineering at the Massachusetts Institute of Technology in 2008, with a focus on premixed combustion dynamics. He has 5 years of industry experience, having held a position as a thermodynamics engineer at ALSTOM and a project manager at ABB.

S53

Plasma based XUV Sources for Metrology Applications

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Compact XUV sources either based on a Laser induced or a discharge plasma offer the opportunity of a wide spread use for applications in the soft x-ray and extreme ultraviolet spectral range. Both concepts are under investigation at the Fraunhofer ILT in Aachen. Currently, the main focus of the work is on improving the systems in order to provide reliable and stable sources for commercial use. This paper reports on considerations for regenerative target systems for Laser induced plasmas with emission around 6.x nm and lifetime studies of discharge based sources with emission around 13.5 nm.

Presenting Author

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

S54

A High-brightness Accelerator-based EUV source for EUV Actinic Mask Inspection

Y. Ekinci, T. Garvey, A. Streun, A. Wrulich and L. Rivkin

Paul Scherrer Institute, Villigen, Switzerland

Actinic inspection on EUV reticles is considered an essential tool for the implementation of EUV lithography in high-volume manufacturing. Nevertheless, there is currently no long-term solution available for it. One of the challenges is the availability of a source with high brightness, stability, and availability. We propose a compact synchrotron light source producing EUV radiation for such metrology applications in the semiconductor industry. Our design is based on a storage ring lattice employing design principles similar to those used in the new family of diffraction limited synchrotron radiation sources. The 430 MeV storage ring of circumference 25.8 m would have an emittance of ~ 6 nm-rad. The required EUV wavelength is obtained using a short period (16 mm) undulator. The concentric storage ring and booster ring enables top-up operation with minimal footprint.

Presenting Author

Dr. Yasin Ekinci is a Group Leader for Advanced Lithography and Metrology at Paul Scherrer Institut in Switzerland.

S55

Actinic Light Source based on LPP for HVM Mask Inspection Applications

Konstantin Koshelev[1,2], Alexander Vinokhodov[1], Oleg Yakushev[1], Alexey Yakushkin[1], Dimitri Abramenko[1], Alexander Lash[1], Mikhail Krivokorytov[1,2], Yuri Sidelnikov[2], Vladimir Ivanov[2], Vladimir Krivtsun[2], Vyacheslav Medvedev[1], Denis Glushkov[3], Pavel Seroglazov[3], Samir Ellwi[3]

1 – RnD-ISAN/EUV Labs, Troitsk, 108840 Russia;
2 – Institute for Spectroscopy RAS, Troitsk, 108840 Russia;
3 – ISTEQ, 5656 AG Eindhoven

In this work we present a product-ready light source based on a renewable Li jet with debris free LPP for use in nanostructure inspections. The closed loop of liquid Li jet with high velocity was used in the source as a target. The primary advantages of lithium as a fuel are its high spectral purity of radiation and the absence of heavy ions. With this target we are using a high temperature self-cleaning method for the input and output windows and a MHD pump for pumping along a closed loop. By employing a jet type of target we have made it a reality to use an infinitely renewable target with excellent spatial stability. Thus removing the need for refilling technology and a complex and unreliable synchronization system of the laser pulse and droplet target. In addition, the use of a collector system with a small NA=0.11 and special jet configuration in the source allows us to dramatically reduce the amount of droplet debris falling on the input and output windows. Self-cleaning technology of output windows based on special SPF allows us to completely prevent the penetration of debris into the collector system. We have achieved conversion efficiency of 1.2%/2π sr at irradiance of 10^{11} W/cm^2. The source rep rate, power and brightness can be optimized according to customer requirements.

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. He has extensive experience working in laser fusion, X-ray lasers and EUV sources. He has worked in these fields in the United Kingdom, Germany, France, Switzerland and the Netherlands.

S56

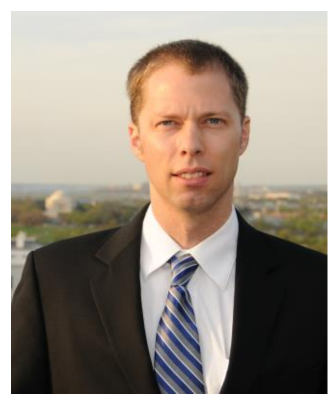
Compact X-ray Sources and Applications for Semiconductor Metrology

R. Joseph Kline

National Institute of Standards and Technology, USA

The semiconductor industry continues to shrink the feature sizes in integrated circuits. The industry is manufacturing the 14 nm node and is transitioning to the 10 nm node. The exact size, shape, and chemical placement of individual atoms in these 3D nanodevices determine the performance of the transistors. Since each circuit can continue billions of transistors that all must work nearly identically for high yield and performance, detailed metrology is critical to development and monitoring of manufacturing processes. The small feature sizes are pushing the limits of current measurements and new measurement technologies are continually being developed and evaluated. X-rays offer a number of advantages for new measurements. The small wavelength of X-rays mean that the feature sizes are larger than their diffraction limit. Some X-ray wavelengths can penetrate through the entire wafer. X-rays also interact with electrons and can provide local chemical and compositional information. Numerous measurements have been demonstrated at synchrotron X-ray sources. These large facilities can provide high intensity and energy tunable X-rays, but are located far away from fabs and do not provide rapid access. Bringing X-ray measurements to the fab will require development of new, compact X-ray sources. This talk will discuss X-ray measurements with the potential to solve critical semiconductor metrology needs and their source requirements. We will then discuss the status of compact X-ray sources and new technologies under development.

Presenting Author



R. Joseph Kline currently leads the Dimensional Metrology for Nanomanufacturing project at NIST. His research interests include X-ray based dimensional metrology of nanostructures for the semiconductor industry and X-ray structure measurements of soft matter systems. He received a Ph.D. in Materials Science and Engineering at Stanford University in 2005, and B.S. and M.S. in Material Science from North Carolina State University in 1999 and 2000, respectively. He has published more than 80 articles, 4 book chapters, and given more than 40 invited presentations. He received the 2012 Presidential Early Career Award for Science and Engineering.

S57

EUV/SXR Spectroscopy of Ge Laser-Produced Plasma

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Laser-Produced Plasmas (LPP) may be used to form EUV/SXR light sources with a high conversion efficiency. The wavelength of the source for EUV lithography was chosen to be 13.5 nm due to the availability of MoSi multilayer mirrors. MoSi multilayer mirrors have a high reflectivity of 72% at 13:52% nm into the bandwidth of the mirrors [1]. Tin LPPs can be used as light sources for EUV lithography because of their high conversion efficiency experimentally ~ 6% [2] and steady state models showing a possible conversion efficiency of ~ 9% [3]. $4p^6 4d^n$ -$4p^5 4d^{n+1}$, $4d^n$ -$4d^{n-1}5p$ and $4d^n$ -$4d^{n+1}4$ f transitions of Sn VII - Sn XIV each form an Unresolved Transition Array (UTA). These UTAs all combine at 13.5 nm [4]. LPPs of Ge emit in this spectral region and could be used as an EUV/SXR light source [5].

In this work the Hartree-Fock with Configuration-Interaction (HFCI) code of Cowan [6] was used to identify previously unreported open 3d transitions of Ge VII - Ge X, and previously identified transitions of Ge VI and Ge VII [7]. The spectra were recorded on an EUV Jenoptik spectrometer with a spectral range of 9.7 to 18 nm. The spectrometer has been wavelength and intensity calibrated at BESSY II. The spectra of Ge plasmas were created with 2 different lasers. A Q-switched Nd:YAG laser with a pulse energy of 978_6 mJ in 5:4_0:3 ns, focused using a 13 cm uncoated BK7 plano-convex lens and a TEA CO2 laser, with a plasma shutter [8] to remove the 2ms N_2 tail, leaving a 50 mJ in 50 ns laser pulse, focused using a 5 cm ZnSe lens. The spectrometer was at 45 degree to the incident laser beam focused normal to a planar target. The experimental rms error on the calibration using known lines of oxygen is ~0:0042 nm. The table below details some of the identified lines within the spectral region. Line identification of Ge VII - Ge X $3p^6 3d^n$ -$3p^5 3d^{n+1}$, $3d^n$ - $3d^{n-1}4p$, 3dn -$3d^{n-1}4$ f of an optically thin Ge plasma will be presented. A comparison between the optically thick Nd:YAG and optically thin CO2 laser-produced plasmas will be given.

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Presenting Author

S58

Colliding Laser Produced Plasmas Analysis: Fast Imaging and Spectroscopic Study

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Creating two laser produced plasmas in close proximity can lead to their collision as they expand. Depending on the separation between the plasmas and the ion-ion mean free path, the two plasmas can interpenetrate or collide and form a stagnation layer [1]. The collision causes kinetic to thermal energy transfer [2], and the formed stagnation layer shows different properties than those of the original plasma, with a longer life time and nearly isothermal temperature distribution along the cylindrical shape [3]. As such, the stagnation layer has shown to be a very suitable target for the laser reheat of a plasma [4], a method used in the EUV lithography industry to increase the CE of the emission in the 2% band at 13.5 nm. To improve coupling of the reheat laser with the stagnation
layer, better understanding of stagnation layer is needed.

In this work we present the evolution of the colliding plasmas and the stagnation layer of a light element Si (Z=14). We view the time resolved expansion of the plasma in the visible region of the spectrum, viewed at 90 degree angle with respect to the expansion direction of the two seed plasmas. The integration time was 10 ns and the time step was 10 ns. An example of an image is shown in Fig. 1. We also present a time resolved spectroscopic study of the stagnation layer in the near ultraviolet region (360-415 nm) and compare the spectrum of single plasma and the stagnation layer.

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Presenting Author

S62

The Electrode-less Z-Pinch as a Metrology Source in the 40-50 nm range

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Recently, there has been interest in the use of VUV wavelength in the 40-50 nm range, for wafer defect inspection and detection. Many systems use 193 nm light, and detect defects such as particles through Mie scattering. As feature sizes have decreased, the size of the "killer defect" – has also decreased. Observing that the Mie scattering amplitude from a particle in this limit scales d^6/λ^4 (d particle size, λ wavelength) one is led to consider light of shorter wavelength. A recent theoretical study[1] concludes that wavelengths in the 40-50 nm range would be particularly effective.

We have considered whether the Energetiq Electrode-less Z-pinch might provide a suitable source. Key questions are the choice of operating gas, and an appropriate operating point. We will show a theoretical study that implies that a Neon plasma of a few eV would provide significant light at these wavelengths.

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Presenting Author

Stephen Horne received his PhD. in plasma physics from the University of Wisconsin, in 1984, and is one of the founders of Energetiq Technology.

S63

High Power Laser-Sustained Plasma Light Sources for KLA-Tencor Broadband Wafer Inspection Tools

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For the last 10 years, the brightness of ultraviolet light sources in K-T Broadband wafer inspection tools increased by orders of magnitude due to advances in LSP technology. Currently, the required average (continuous) source spectral radiances are measured in Watts per mm2·nm·srad and powers in the intermediate focus – in hundreds of Watts. KLA-Tencor explores applications of LSP in UV-DUV-VUV spectral ranges. In this talk, we discuss source requirements and challenges of high-power LSP operation.

Presenting Author

Ilya Bezel is a Principal Research Scientist in KLA-Tencor Corporation in Milpitas, California. After graduating from Moscow Institute of Physics and Technology (MPTI) in 1994, he received Ph.D. in Physical Chemistry from University of Southern California, Los Angeles studying ultrafast decomposition dynamics of small polyatomics. He was a Miller Fellow at UC Berkeley in 2000-2003 investigating electron localization at metal surfaces and later a Director's Fellow in Los Alamos National Laboratory working in the field of nanotechnology. Since 2005 he has been conducting research and development of broad-band light sources for wafer inspection at KLA-Tencor Corp.

S64

High-brightness Broadband Light Source for Various Industrial Applications

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2. ISTEQ, 5656 AG Eindhoven

Our current XWS-65 light source product has been specially developed for a variety of applications, including spectroscopy, high resolution microscopy, film measurement, surface metrology and others. This source is based on cutting edge technology: producing extremely high brightness across wavelengths ranging from 190nm-2500nm along with high stability and long lifetime.

We are currently working to increase the brightness of the source by a few factors.
Due to the extensive experience we have along with our high profile partners in the field of light source development (DPP and LPP) we can address any requirements set by the industry.

Presenting Author

S71

Soft X-ray Microscopes for Biology: The Source

Gerry McDermott, Ph.D.

Department of Anatomy, UCSF and Lawrence Berkeley National Laboratory

Soft x-ray microscopes are in high demand by biologists wanting to visualize and quantify cells. In particular, biologists want to image their specimens in 3D using tomographic methods. Soft X-ray tomography (SXT) overcomes inherent limitations in light- and electron microscopies and generates unique insights into the sub-cellular world. Unfortunately, the expansion of SXT is limited by source availability. To date, soft x-ray microscopes for SXT have relied on synchrotron-generated illumination. This, of course, restricts microscopes to being sited in a small number of geographical locations, with further limitations being imposed by the fierce competition for space on the synchrotron experimental floor. Laboratory scale soft x-ray sources have enormous potential in terms of SXT. In this talk, I will discuss – from an end user perspective – the illumination characteristics biologists want when they are imaging cells by SXT.

Presenting Author

Gerry McDermott is a Research Biophysicist in the Department of Anatomy, UCSF and a Senior Scientist Affiliate at Lawrence Berkeley National Laboratory. He has spent most of his career applying synchrotron-based x-ray techniques to biological research. Initially, his main interest was using hard x-rays to determine the crystallographic structure of membrane proteins. Most recently, his focus has shifted to using soft x-ray tomography as a method for visualizing and quantifying cells and their sub-cellular organization.

S72

Chromatin Reorganization during Viral Infection

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Lytic infection with herpes simplex virus type 1 (HSV-1) induces profound modification of the cell nucleus including formation of a viral replication compartment and chromatin marginalization into the nuclear periphery. We used three-dimensional soft X-ray tomography (SXT), combined with cryogenic fluorescence, confocal and electron microscopy, to analyze the transformation of peripheral chromatin during HSV-1 infection. The random step modeling of HSV-1–sized particles in a 3D SXT reconstruction of infected cell nucleus demonstrated that the peripheral compacted chromatin layer restricts viral capsid diffusion. The SXT data showed an increased presence of low-density gaps in the marginalized chromatin at late infection. These results demonstrated that HSV-1 infection induces the formation of channels penetrating the compacted layer of cellular chromatin and allowing for the passage of progeny viruses to the nuclear envelope, their site of nuclear egress.

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Presenting Author

Dr. Maija Vihinen-Ranta is Associate Professor in *University of Jyvaskyla, Jyvaskyla, Finland since 2011.* She received her Ph.D from University Jyvaskyla (JYU) in 1998. She did her Post-doc work at James A. Baker Institute for Animal Health, Cornell University, Ithaca, New York, USA.

S73

Exploring the Soft X-ray Radiance of Laser Plasmas

Fergal O'Reilly & Gladson Joseph

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Illuminating micron-scale objects for nano-imaging is a challenging area of technology, particularly in the soft x-ray region of the spectrum. Optimizing emission from laser plasmas for soft x-ray microscopy requires understanding the limitations on both the total flux and the spatial extent of the emitter in the desired wavelength range. Recent results are presented from laser plasma imaging and spectroscopy give us some good insight into the trade-offs in spectral radiance as a function of the driving laser parameters and the laser target material.

A range of metal targets was illuminated with pulses from a 7-ns, 800-mJ, Nd:YAG laser at normal incidence. Spectra were recorded on a 0.25-m grazing incidence spectrometer fitted with a flat-field grating which had a nominal groove density od 1200/mm. Images were recorded using a range of pinholes combined with filters to select the wavelength range.
Plasma sizes below 20 μm were observed and trends in plasma behavior as a function of target material and laser parameters deduced.

Presenting Author

S74

Laboratory Tomographic Microscopy with Compact Plasma based Extreme ultraviolet and Soft X-ray Sources

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The commonly used sources of water window radiation (wavelength: 2.3 - 4.4 nm) are synchrotrons which has limited access and are expensive [1, 2]. A compact soft x-ray (SXR) source based on gas-discharge plasma, was developed in Fraunhofer Institute for Laser Technology together with RWTH Aachen University. This source produces a highly monochromatic line emission at 2.88 nm, using nitrogen gas suitable for water window microscopy. In the water window spectral range light interaction with biological cells provides a natural contrast used for imaging in x-ray microscopy [3]. 2D images with resolution down to 40 nm and 1000 magnifications have been successfully taken [3]. Currently, 2D images of a dried neuron cell were obtained with a good contrast of carbon-rich internal structures of the cell. For three-dimensional imaging, this setup will incorporate a capillary-type sample holder that allows for 180° rotation of biological samples. Different projections of the samples will be taken and used for reconstruction of tomographic images of biological cells.

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Presenting Author

Mr. Daniel Vicario is a candidate for the Joint Doctorate Erasmus Mundus EXTATIC PhD program for Experimental Physics with RWTH Aachen as the home university and University College Dublin as the host university. He obtained his BS degree with an outstanding graduate award in Applied Physics major in Instrumentation from the College of Science, University of Santo Tomas (UST) in the Philippines. He finished his M.Sc. degree in Applied Physics major in Medical Physics at The Graduate School, also in UST.

S75

Relativistic Plasma Control using Two-colour Fields

Brendan Dromey*[1], Mark Yeung[1], Sergey Rykovanov[2], Jana Bierbach[2,3], Lu Li[1], E. Eckner[3], Stephan Kuschel[2,3], Abel Woldegeorgis[2,3], Christian Rödel[2,3,4], Alexander Sävert[3], Gerhard G. Paulus[2,3], Mark Coughlan[1], and Matthew Zepf[1,2,3]

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The interaction of a sufficiently intense laser pulse with an initially solid target can result in the formation of a plasma in which surface electrons are accelerated to relativistic speeds on time scales shorter than a laser cycle. These electrons can form dense bunches and emit radiation that is upshifted in frequency relative to that of the incident laser pulse, reaching up to extreme-ultraviolet (XUV) or even X-ray photon energies [1,2]. As this process repeats periodically with the laser, this upshifted radiation is emitted in the form of high harmonics of the laser frequency. Here, we show clear experimental data demonstrating that this process can be controlled by converting part of the incident laser energy into its second harmonic before it is incident on the target surface. Fine tuning of the sub-cycle timing of this second harmonic pulse can significantly alter the shape of the incident waveform, which modifies the trajectories of the electrons, and can lead to a dramatic increase of the efficiency at which energy is converted into XUV radiation [3]. As well as providing insights into the relativistic dynamics of surface electrons in these interactions, this has the potential to lead to new laser based, coherent XUV sources with unprecedented pulse energies and even attosecond scale pulse durations.

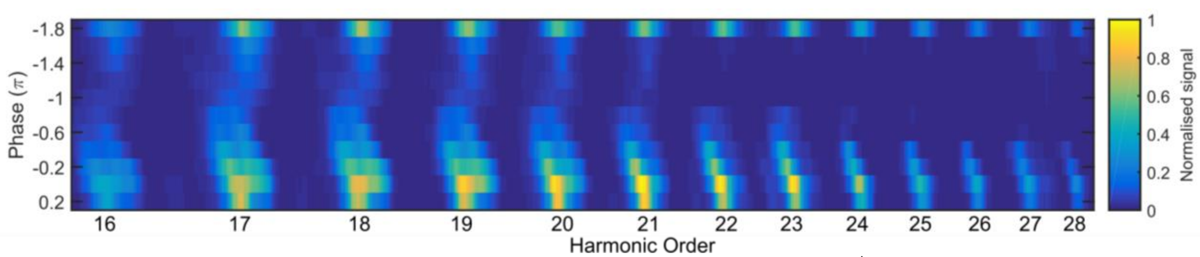

Figure 1. Experimentally observed high harmonic signal for different phases of the 2nd harmonic relative to the fundamental laser pulse. Tuning the phase controls the harmonic generation efficiency and the highest order observed which is directly linked to the dynamics of the relativistic electrons in the target.

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[3] M. Yeung *et al.*, Nature Photon. 11, 32 (2016)

Presenting Author

Brendan Dromey graduated from his BSc in UCD in 2001. After completing an MSc in the UCD Spectroscopy group in 2002, Brendan moved to Queen's University Belfast to undertake a PhD in the Centre for Plasma Physics. While there he developed novel experimental approaches for studying the emission of coherent extreme ultraviolet and soft X-ray radiation from relativistically intense laser solid interactions. Most notably his work verified that in reflection the emission can best be described by the theory of relativistic spikes resulting in several seminal publications in both Nature Physics and Physical Review Letters. After completing his PhD in 2005 Brendan continued working in the field of intense laser-matter interactions studying the microscopic mechanisms for the generation of coherent radiation. This resulted in two visiting positions in the Max Planck Institute for Quantum Optics in Garching (Munich). After these Brendan return to Queen's University Belfast on a Career Acceleration Fellowship which saw him become a full time member of academic staff in 2011 as a lecturer. He was promoted to Reader/Associate Professor in 2015 and is the acting Director of Impact for the School of Mathematics and Physics. His research interests now range from ultrafast laser development to the generation of coherent extreme ultraviolet and soft X-ray radiation from both solid and gas targets and more recently he has developed new techniques for studying the ultrafast interaction of ions in matter.

S76

Spectroscopic EUV reflectometry for characterization of thin films systems and determination of optical constants

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Modern nanotechnology is continuously raising demands on quality and purity of thin films and interlayer interfaces. As thicknesses of employed layers decrease to single nanometers, traditional characterization tools struggle to satisfy simultaneously throughput, precision and non-destructibility requirements. Spectroscopic reflectometry with extreme ultraviolet radiation (EUV, 5-40 nm wavelengths) allows for non-destructive study of surfaces and controlling in-depth structure of the produced materials. A laboratory tool is developed that is capable of multi-angle (2°-15°) and spectrally broadband (9.5-17 nm) extreme ultraviolet reflectometry at grazing incidence combined with a reduced sample illumination spot size, enabling spatially resolved metrology. Suitability of the tool to the industrially relevant applications such as analysis of surface contamination, will be illustrated by results of experiments with test samples exposed to real EUV source operation environment. The technique shows high chemical sensitivity, and the results correlate with that of photoemission electron microscopy. Reflectance spectra of the probed materials feature characteristic absorption edges with their fine structure which offers a possibility to gain additional information about chemical composition. Collection of spectral “fingerprints” and analysis of near-edge reflectance of samples have been done additionally at the ELETTRA synchrotron facility, Trieste. The investigation results of the $LaLuO_3$ (high-k material) films of different crystallinity will be presented and discussed with the focus on the angularly and spectrally resolved EUV reflectance study as a method for structural characterization and as a basis for the refractive index determination.

Presenting Author

S77

A compact, desk-top near edge soft X-ray absorption fine structure spectroscopy system based on a laser plasma double stream gas puff target source

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A compact, desk-top, near edge soft X-ray absorption spectroscopy system was developed based on a laser-plasma source with double stream gas puff target. The krypton/helium plasma is formed by interaction of a laser beam with double stream gas puff target. The laser plasma source was optimized for efficient emission from 1.5 to 5 nm wavelength in the soft X-ray region. Such emission is used to acquire simultaneously spectra of soft X-ray light from the source and from the investigated sample using grazing incidence spectrometer. The measurements in transmission mode reveal the fine structures near the carbon K-α absorption edge of thin mylar film. The data are in agreement with synchrotron measurements. From those small features the composition of the sample was successfully obtained.

Presenting Author

S81

REFURBISHMENT OF COLLECTOR MIRRORS FOR WATER WINDOW MICROSCOPY

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Presenting Author

S82

EUVL Optics for Free Electron Laser Sources: Damage Threshold Studies and the Use of Adjusted Wavelengths

Eric Louis

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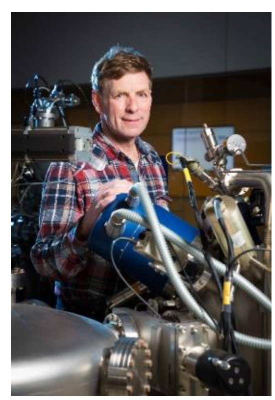
Today, high rep rate laser produced plasma sources are the most likely candidates for EUVL. However, free electron lasers show potential to provide at least equal EUV power while at high spectral purity. Another advantage of FEL sources is the possibility to tune the wavelength to take advantage of increased transmission of the multilayer optical system. Using a wavelength closer to the Si absorption edge results in a significant increase of the total multilayer reflectance without loss of bandwidth, due to an anomalous effect of the optical constants.

Yet, having typically 10-100 fs pulse lengths, the EUV power density on the optics is substantially higher than in the ns-laser plasma case and there is a risk of damaging the optics.

Extensive damage experiments were done at FLASH, the Free Electron Laser in Hamburg, to test the radiation resistance of coatings, both under normal and grazing incidence conditions, including a study on the possible damage mechanisms.
Results will be presented on both the use of an adjusted wavelength and the determination of the damage threshold.

Presenting Author



Eric Louis carried out research and development of EUV and soft X-ray multilayer reflective coatings since 1992. Initially at the FOM-Institute for Plasma Physics Rijnhuizen, later DIFFER, and since 2014 in the Industrial Focus Group XUV Optics of the MESA+ Institute for Nanotechnology of the University of Twente in Enschede, the Netherlands. He worked on multilayers for several applications such as space research and synchrotron applications, but focused his research primarily on EUV and beyond-EUV multilayers for lithography. Eric Louis has been responsible for research, development and the coating of several optics for the first EUV lithography tools now operational in semiconductor industry. Furthermore he worked on layer smoothing mechanisms, stress mitigation, suppression of out of band radiation, lifetime issues and damage mechanisms when single and multilayer optics are exposed to extremely high photon fluxes.

S84

Novel Spectrometers for Broad-band Characterization of EUV-Emitting Plasmas

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The spectral region ranging from soft X-ray to vacuum ultraviolet is currently being intensively explored for numerous important applications, including water-window microscopy, material science, lithography and metrology for fabrication of next generation integrated circuits. A promising technology for creating high-power sources of short-wavelength radiation is based on the use of high-temperature dense plasmas of high Z elements, e.g. tin, xenon or bismuth. Such plasma sources typically produce a broad emission spectrum due to numerous optical transitions of different ions in the plasma. At the same time real applications typically rely on a relatively narrow band from this wide emission spectrum; in some case the rest of the radiation can be harmful. Optimization and control of the operation of short-wavelength radiation sources requires simple and reliable spectral characterisation of the plasma emission. Here we present two designs of compact spectrometers operating in the reflection regime. The first spectrometer covers an extremely broad spectral range 5-200 nm and possesses moderate spectral resolution $\lambda/\Delta\lambda \approx 50$. This spectrometer uses CCD for the registration. Thus such a spectrometer can be used for the search of strong emission bands over the broad spectral range for various plasma conditions. The second spectrometer is optimised for operation in the 10-40 nm wavelength range and possesses high spectral resolution $\lambda/\Delta\lambda \sim 200\text{-}400$. This spectrometer is compatible both with CCD and MCP detectors. The application of MCP as the detector allows temporally resolved spectral measurements. Application of the spectrometers for the characterisation of radiation sources is exemplified for different experimental conditions.

Presenting Author

Viacheslav Medvedev is project coordinator at RnD-ISAN/ISTEQ. He received his PhD from the University of Twente, XUV Industrial focus group. Viacheslav has research experience in the field of sources and optics for short-wavelength radiation, including soft X-rays and EUV.

S85

Broadband Spectral Characterization of EUV light Sources with a Transmission Grating Spectrometer

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Extreme ultraviolet (EUV) lithography light sources are aimed to emit light in a narrow wavelength band (in-band: 13.5 nm ± 1%) that is matching the spectral transmission of the optics and sensitivity of the photoresist. On the other hand, these sources also emit radiation outside the desired wavelength band, extending into the deep ultraviolet (DUV) and visible/IR range. The out-of-band radiation can have significant side effect such as contrast loss in the exposed photoresist or heat load on the delicate optics. Moreover, spectral characteristics of the in-band and out-of-band ranges contain a wealth of information about the conditions of the plasma. A broadband spectral diagnostic can be a vital tool in assessing the side effects of the out-of-band radiation and optimizing the plasma conditions towards higher in-band and lower out-of-band emission. Here we present spectral measurements of an EUV lithography source in the EUV and DUV/visible wavelength ranges using a transmission grating spectrometer. The spectrometer is based on a set of free-standing transmission gratings that can be reconfigured to record EUV and DUV/visible bands without breaking the vacuum. The recorded spectra can be immediately related to specific charge states in the plasma allowing optimization of the source conditions.

Presenting Author

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An Extreme Ultraviolet Monochromator for use with a Laser Produced Plasma Source

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This poster presents the design and construction of a Czerny-Turner (CT) grazing incidence monochromator[1] to be used with a laser produced-plasma light source. The combination is designed to be suitable for photoelectron spectroscopy (PES) experiments [2] in the extreme ultraviolet (EUV)/soft-x ray spectral range. The monochromator is based on a two-mirror-plus-grating grazing incidence CT design. An unexpected, large deviation in some of the optical elements used in this work from the specifications provided by the manufacturer meant that the initial design did not deliver the expected, or required, performance. A thorough re-design was performed and tested. The system was simulated using Zemax® ray-tracing software, which aided in identifying the optimum trade-off between throughput, bandwidth and brightness.

A number of targets for the laser plasma source was investigated, leading to the identification of tungsten as the optimum target for use with a ~800-mJ, 7-ns laser pulse to generate radiation in the 7 – 17 nm range. Conditions pertaining in the tungsten LPP were identified with the aid of previously published work [3 and references therein].

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[3] C. S. Harte, T. Higashiguchi, T. Otsuka, R. D'Arcy, D. Kilbane, and G. O'Sullivan, "Analysis of tungsten laser produced plasmas in the extreme ultraviolet (EUV) spectral region," Journal of Physics B: Atomic, Molecular and Optical Physics, vol. 45, no. 20, p. 205002, 2012.

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