2019 Source Workshop

November 4-6, 2019
Amsterdam ▪ The Netherlands

Workshop Abstracts

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Organized by

Vivek Bakshi (EUV Litho, Inc.), Chair

Oscar Versolato (ARCNL), Co-Chair

Joost Frenken (ARCNL), Co-Chair

Welcome

Dear Colleagues;

I am looking forward to welcoming you to Amsterdam for the 2019 Source Workshop. This year's workshop is co-organized with ARCNL and we have added an additional full day of agenda to the workshop. On Monday, in addition to a plasma modeling and code comparison session, we will have showcase presentations from ARCNL as well as a lab tour.

Source workshop, now in its 10th year, is the largest annual gathering of EUV and XUV source experts! In addition to EUV sources topics include, Blue- X (EUVL extension via short wavelength sources and optics), optics, lasers and metrology. The workshop proceedings will be published online on our website www.euvlitho.com and made available to all.

I will like to thank Source workshop's co-chairs from ARCNL (Oscar Versolato and Joost Frenken) for their help in the organization of the workshop. I will also like to thank the source technical working group (TWG), workshop support staff, session chairs and presenters for their part in making the workshop a success. I look forward to your participation in the workshop.

Best Regards

Vivek Bakshi
Chair, 2019 Source Workshop

Source Technical Working Group (TWG)

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Eric Louis (University of Twente)
Slava Medvedev (Institute for Spectroscopy RAS)
Hakaru Mizoguchi (Gigaphoton)
Fergal O'Reilly (UCD)
Gerry O'Sullivan (UCD)
Yuriy Platonov (RIT)
Ladislav Pina (Rigaku and CTU)
Jorge Rocca (University of Colorado)
Akira Sasaki (JAEA)
Craig Siders (LLNL)
Atsushi Sunahara (Purdue)
Yusuke Teramoto (BLV Licht)
Hironari Yamada (PPL)
Mikhail Yurkov (DESY)
Oscar Versolato (ARCNL)

Vivek Bakshi (EUV Litho, Inc.) - Chair

ABSTRACTS

S1

EUV Source for Lithography in HVM: Performance and Prospects

Igor Fomenkov

ASML US LP, San Diego, CA 92127, USA

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.

S2

Challenge of High Power LPP-EUV Source with Long Collector Mirror Lifetime for Semiconductor HVM

Hakaru Mizoguchi

Gigaphoton Inc., Hiratsuka Kanagawa,254-8567, JAPAN

Gigaphoton develops CO_2-Sn-LPP EUV light source which is the most promising solution as the 13.5nm high power light source for HVM EUVL. Unique and original technologies including; combination of pulsed CO_2 laser and Sn droplets, dual wavelength laser pulses for shooting and debris mitigation by magnetic field have been applied. We have developed first practical source for HVM; "GL200E" [1)] in 2014. Then it is demonstrated which high average power CO2 laser more than 20kW at output power in cooperation with Mitsubishi Electric[2)]. Pilot#1 is up running and it demonstrates HVM capability; EUV power recorded at 111W on average (117W in burst stabilized, 95% duty) with 5% conversion efficiency for 22 hour operation in October 2016[3)]. Availability is achievable at 89% (2 weeks average), also superior magnetic mitigation has demonstrated promising mirror degradation rate (= 0.5%/Gp) at 100W or higher power operation with dummy mirror test. We have demonstrated actual collector mirror reflectivity degradation rate is less than 0.4%/Gp by using real collector mirror around 125W (at I/F clean) in burst power during 30 Billion pulses operation. Recently we have redefined target power higher >330W and its development plan[4)]. Also we will update latest challenges for >330W average operation with actual collector mirror at the conference.

Reference

1) Hakaru Mizoguchi, et. al.: "Sub-hundred Watt operation demonstration of HVM LPP-EUV source", Proc. SPIE 9048, (2014)

2) Yoichi Tanino et.al.:" A Driver CO2 Laser Using Transverse-flow CO2 Laser Amplifiers", EUV Symposium 2013, (Oct.6-10.2013, Toyama)

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

4) Hakaru Mizoguchi et al.:" High Power LPP-EUV Source with Long Collector Mirror Lifetime for Semiconductor High Volume Manufacturing", Proc. SPIE 10957, Extreme Ultraviolet (EUV) Lithography X (2019) 10957-39

Biography

Presenting Author

Hakaru Mizoguchi is a Fellow of SPIE and also member of The Laser Society of Japan and The Japan Society of Applied Physics. He received a diplomat degree in plasma diagnostics field from the Kyushu university, Fukuoka, Japan in 1982 and join Komatsu ltd.. He joined CO2 laser development program in Komatsu for 6 years. After that he was 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 present position. He got Sakurai award from OITDA Japan in 2018.

S23

Collector Mirrors for the Water-window

Torsten Feigl[a], Marco Perske[a], Hagen Pauer[a], Tobias Fiedler[a], Philipp Naujok[a]
Christian Laubis[b], Michael Kolbe[b], Frank Scholze[b]

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Multilayer developments for the water window spectral region (2.3 nm to 4.4 nm) are mainly triggered by fundamental research applications based on synchrotron or FEL sources. In recent years, increasing power and brightness of table-top laboratory soft X-ray sources enhance greatly the number of their applications in both, fundamental and applied research. Water window microscopy is as an outstanding example of new applications. Lessons learned for both source and optics development can greatly be used for future Blue-X applications.

This paper reviews recent multilayer optics developments at optiXfab for the water window and focusses on two aspects: Imaging performance of multilayer optics and refurbishment of water window collector mirrors.

Presenting Author

Torsten Feigl studied physics in Jena, Germany, and in Paris, France. He graduated with a PhD in physics from the University of Jena in 2000. Tor-sten Feigl joined Fraunhofer IOF in 1994 working on design, manufacturing and characterization of optics for the extreme ultraviolet spectral range and X-rays. For more than ten years he was leading the "EUV and soft X-ray optics" working group at the Fraunhofer IOF. In 2013 Torsten Feigl founded optiX fab, a Fraunhofer IOF spin-off company. Located in Jena, Germany, optiX fab is currently supplying chipmakers, EUV tool and source manufacturers as well as institutes, universities, synchrotron beamlines and EUV research consortia worldwide with customized multilayer and grazing incidence optics for EUV lithography applications at 13.5 nm and the entire XUV, soft and hard X-ray spectral range.

S24

Optical Properties of Multilayers for Operational Wavelengths between 6.6 and 13.5 nm

A.E. Yakshin, A.A. Zameshin, D. Kuznetsov, I. Milov, I. Makhotkin, E. Louis, and F. Bijkerk

Industrial Focus Group XUV Optics, MESA+ Institute for Nanotechnology, University of Twente

EUV Lithography systems operating with 13.5 nm light have successfully been developed and built and techniques to improve the resolution have been identified. For future applications, the operational wavelength of the litho systems can be further reduced to enhance the resolution, provided a sufficiently high reflectance and bandwidth, both in wavelength and angle, can be achieved. These shorter wavelengths are not, or not yet, on the roadmap of the semiconductor industry. However, the multilayer community and source developers need to be ready for a possible further reduction of the wavelength. In this talk we will discuss optical properties, challenges and some results of reflective optics between 6.6 and 13.5 nm

Presenting Author

Andrey Yakshin is a Senior Scientist at University of Twente, MESA+ Institute for Nanotechnology. In 1996 he received his Ph.D. from University of Aix-Marseille III and performed post-doctoral research at the Institute of Microelectronics Technology RAS. Since 1998 he is involved in multilayer optics research at FOM-insitute for Plasma Physics Rijnhuizen and since 2014 he continues at University of Twente. His field of expertise is in material science of thin films and multilayer structures. Yakshin published over 90 journal articles and 15 patents. Many of his developments have found industrial application.

S25

Progress on a High Radiance Water Window Source for Imaging

F. O'Reilly[1,2], W. Fyans[2], S. Brady[2], A. Manzoni[2], D. Rogers[2], J. Howard[1,2], D. Skoko[2], M. Donnellan[2], K. Wilson[2], J. Costello[2], I. Tobin[2], T. McEnroe[2], K. Fahy[2] and P. Sheridan[2]

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[2]SiriusXT Ltd., 9 Holly Ave, Stillorgan Business Park, Dublin, Ireland

Laser plasma based soft x-ray sources based on medium to high atomic number targets can produce high radiance broadband output suitable for translating synchrotron-based techniques in 3D imaging and spectro-microscopy to the laboratory scale. One difficulty encountered in using these plasmas is the prodigious amount of debris that they produce. The presentation will detail various aspects of the UCD School of Physics/SiriusXT Ltd soft x-ray beamline, which uses liquid coated optics to overcome the debris challenge and will focus on the system optical performance and how that relates to applications.

Presenting Author

S26

Further Enhancement of the Xe LPP 11-nm Radiation Source Efficiency – A Study of the Laser-energy Absorption at Varied Parameters of the Gas-target Irradiation

P. S. Butorin, S. G. Kalmykov, V. A. Maximov, M. E. Sasin

Ioffe Institute, St. Petersburg, Russia

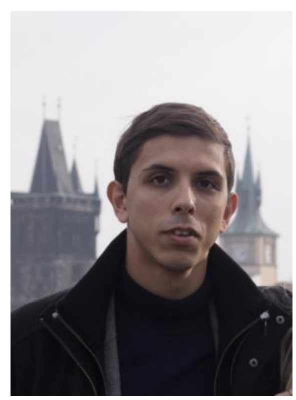
At the Joffe Institute, studies of the Xe laser plasma considered a promising λ≈11nm radiation source for the EUV lithography are ongoing. *CE* = 3.9% at *λ* = 11.2 nm attained by now [*S. Kalmykov et al.. To be published in J. Appl. Phys.* ***126*** *(2019)*] stimulates to a further source optimization effort. The present work is aimed at investigating the laser energy absorption in the plasma.

Earlier we reported that irradiation of the Xe gas-jet target with a wide, defocused laser beam resulted in a dramatic increase of the EUV output. This is why in the present study, measurements of the laser light absorption have been performed at a diversity of irradiation configurations and laser pulse energies. The results turned out completely non-trivial: the absorbed portion varied within 3-7 times subject to the experimental conditions above, with its minimum value being only 9% for the beam tightly focused onto a vicinity of the jet axis. Another interesting fact was what a ratio of the emitted EUV radiation to the absorbed laser energy was only slightly (≤20%) changing over a wide span of the jet-focus relative positions.

At present, an analysis of these results is in progress, nevertheless, ample possibilities to control the conversion efficiency can be seen.

Presenting Author

Butorin Pavel is a PhD student at the Ioffe Institute (St. Petersburg, Russia) where he is a regular member of a group, which develops a Xe laser-plasma 11-nm radiation source. He obtained his master's degree in plasma physics at the Peter the Great St. Petersburg Polytechnic University. His research interests include plasma physics, physics of lasers and spectroscopy.



S27

Scaling of Electron Temperature and Soft x-ray Intensity in Laser-produced Heavy Element Highly Charged Ions

Hiromu Kawasaki,[1] Atsushi Sunahara,[2] Yuta Shimada,[1] Takeo Ejima,[3] Weihua Jiang,[4] Gerry O'Sullivan,[5] Masaharu Nishikino,[6] Shinichi Namba,[7] and Takeshi Higashiguchi[1]

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EUV and soft x-ray sources are very important to study radiation hydrodynamics, opacities, photo-ionized plasmas, and plasma diagnostics. There is particular interest in the relationship between electron temperature and emission spectra, which result from the balance between the emissivity and opacity in the spectral region of interest. On the other hand, it is important to understand the energy flow, related to the radiation transport, by highly charged ions (HCIs) in heavy element (high-*Z*) plasmas. We successfully achieved an optically thin state in laser-produced heavy element plasmas at determined electron temperatures, which have been predicted by the power balance and the collisional-radiative models. We also mapped the power-loss processes in sub-ns and ns laser-produced high-*Z* plasmas. The electron temperature evaluation was in good agreement with the power balance model and was supported by the spectral analysis. The output flux in the soft x-ray region was stronger at higher critical density.

Presenting Author

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

S28

Optimized Highly-charged Ion Production for Strong Soft X-ray Sources with UTA Spectra

Yuta Shimada,[1] Hiromu Kawasaki,[1] Kanon Watanabe,[2] Hiroyuki Hara,[1] Kyoya Anraku,[1] Misaki Shoji,[1] Toru Oba,[3] Masaru Matsuda,[4] Weihua Jiang,[5] Atsushi Sunahara,[6] Masaharu Nishikino,[7] Shinichi Namba,[8] Gerry O'Sullivan,[9] and Takeshi Higashiguchi[1,2]

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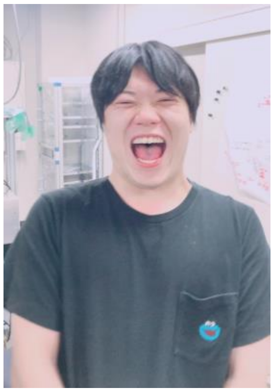
[7]Kansai Photon Science Institute, National Institutes for Quantum and Radiological Science and Technology (QST), Kizugawa, Kyoto 619-0215, Japan

We studied optimized emission from strong sources based on unresolved transition array (UTA) emission. The peak UTA wavelengths follow a quasi-Moseley's law as $\lambda = 33.82 \times R_0^{-1} (Z - 20.86)^{-1.61}$ nm for a critical density of 1×10^{21} cm^{-3} and $\lambda = 165.8 \times R_0^{-1} (Z - 12.44)^{-1.94}$ nm for a critical density of 4×10^{21} cm^{-3}, respectively. The photon flux decreased with increasing atomic number. We also mapped the optimum electron temperatures and corresponding charge states required to produce strong EUV/soft x-ray UTA emission with the photon flux of the order of 10^{14} photons/nm/sr. The present quasi-Moseley's law is sufficient for identifying the optimum element for numerous applications, such as material ablation and ionization, nano-lithography, and *in vivo* biological imaging in the water-window soft x-ray spectral region.

Presenting Author



Yuta Shimada is a graduate student in engineering at the Utsunomiya University. His research activities have focused on the *Z*-scaling of the UTA spectra and laser parameter dependence in the plasmas for short-wavelength light sources.

S31

Status of EBL2, an EUV irradiation facility at TNO and upcoming upgrades (Invited Presentation)

Norbert Koster, Herman Bekman, Michel van Putten, Rory de Zanger, Rob Ebeling, Arnold Storm, Chien-Ching Wu, Jetske Stortelder, Peter van der Walle, Jochem Janssen

TNO, The Netherlands

EUV lithography is now being used in high volume production for the 7 nm node. The roadmap for the semiconductor industry extents to 2 nm and beyond. To enable this it is necessary to continue the development of EUVL with respect to EUV source power, High NA optics, pellicles and new absorbers for the photomasks. To enable this research TNO has realized EBL2, an irradiation facility for EUV exposures to help industry in developing EUV pellicles and absorbers, as well as study life time of optics and photomasks at intensities which are to be expected in the present and new scanners for EUVL. EBL2 uses a tin fueled EUV source in order to have a similar pulse length, shape and spectrum as a EUV scanner of ASML. Samples can be exposed to various doses/intensities of EUV light in different conditions. Various process gasses can be introduced in a broad range of partial pressures and sample temperature can be controlled. In-situ imaging ellipsometry and in-situ X-ray Photoelectric Spectroscopy is available to track surface changes/modifications. Additionally, the setup can be used to characterize EUV-induced plasma, which is the result of the high photon flux in the focussed beam of EBL2.

In the presentation we will discuss the design and layout of EBL2 and show some results obtained during the validation process. The second part of the presentation will be about future developments; An absorber test program to validate these absorbers for acceptance in scanners has been set up together with ASML. The installation of a new collector is planned for Q4 2019, which will further increase the peak intensity and power at sample level. Additionally we are developing new functionality for the system with in-situ reflectometry and IR microscopy to enhance the analysis capabilities of EBL2.

Presenting Author

Norbert Koster is Principal Scientist at TNO in the group for Nano-instrumentation, he has worked in vacuum technology and EUV lithography since 1992. After graduation he worked at the former FOM Institute for Plasma Physics Rijnhuizen. There he was involved in the fabrication and optimization of Multilayer Mirrors for EUVL applications and space astronomy as well as the improvement of the deposition tools. In 1999 he started at TNO as vacuum engineer. Together with ASML and partners he stood at the birthplace of the EUV Alfa demo tools and their successors. One major part of this was the development of ultra clean vacuum (UCV) technology needed to ensure vacuum system cleanliness and optics life time. During his career he developed interest in vacuum engineering, systems engineering, plasma science and contamination control. As Principal Scientist he is involved in projects for EUV Lithography, plasma technology, contamination control and nuclear fusion (ITER). He developed several methods to measure contamination in vacuum systems, which resulted in a number of patents, systems and presentations. His current topic of interest is contamination control for optical systems which use highly energetic particles like ions, electrons and photons. Recently he was deeply involved in the realization of a new EUV exposure facility (EBL2) for EUV optics lifetime research at TNO in Delft.

As Principal Scientist, he is also involved in the development of the scientific and strategic programs of TNO and several research programs in the department Nano-instrumentation. He is a member of the Dutch vacuum society NEVAC, the American Vacuum Society (AVS) and the International society for optics and photonics (SPIE).

S32

Laboratory XUV GI Optics and Metrology (Invited Presentation)

Ladislav Pina

Rigaku

GI mirror collectors and collimators have been designed and tested. Applications include water window microscopy and XUV spectroscopy. Relevant XUV detectors and cameras have been also developed. Examples of results from XUV source imaging, XR microtomography and ultra-high resolution XUV microscopy are presented.

Presenting Author

S33

XUV Scatterometry and Fluorescence for Nano-structured Surfaces (Invited Presentation)

Frank Scholze

PTB, Department Radiometry with Synchrotron Radiation, Berlin, Germany

For more than 30 years, the Physikalisch-Technische Bundesanstalt (PTB), the German national metrology institute, is strongly engaged in the field of metrology using synchrotron radiation. This research program started together with the user operation of the electron storage ring BESSY I in the early 1980's in Berlin. At the beginning, the work was focused on fundamental radiometry, i.e. using the storage ring as a primary radiation source standard. Meanwhile, at the electron storage rings BESSY II and the Metrology Light Source (MLS) in Berlin-Adlershof, the activities have been extended to a broad range of fundamental and applied photon-based metrology beyond basic radiometry in the spectral range from far infrared to hard X-rays, including methods like reflectometry and X-ray fluorescence and absorption spectroscopy and small angle scattering as well. The advance of semiconductor structures continuously challenges the available metrology capabilities. PTB therefore explores possible EUV and XUV-based metrology approaches for the characterisation of nano-structured surfaces.
On the other hand, with the development of EUV Lithography to HVM, the industrial application of EUV and XUV radiation matured and was significantly brought forward. This will enable to bring synchrotron radiation based metrology approaches to the laboratory and finally to the fab. Examples of recent investigations in the field of dimensional metrology on nano-structured surfaces, performed within the framework of scientific co-operations with external partners from industry and research will be presented. The advantages of scatterometry in the EUV and soft X-ray spectral ranges (about 1 nm to 20 nm) and potential paths for further developments are discussed.

Presenting Author

Frank did his Physics studies at TU Dresden from 1982-87 and graduated with a work on x-ray fluorescence analysis. In 1997 he received PhD at TU Berlin on the topic of internal quantum yield of silicon in the soft X-ray spectral range. From 1987-91 he worked on x-ray detectors at the Centre for scientific instrumentation of the Academy of Sciences. Since 1991 he has been with PTB at BESSY and working on EUV and soft x-ray detector calibration and optical components characterization, development of measurement methods for the characterization of components for EUV Lithography and x-ray scattering methods for the characterization of structured surfaces. Since 2004 he is the Head of the working group "EUV radiometry" and since June 2019 Head of the Department "Radiometry with Synchrotron Radiation." His work interests are the characterization of optical properties of materials and optical components and basic physical effects in the UV to soft X-ray spectral ranges and investigation of new metrology approaches for nano-structured surfaces using UV to soft X-ray radiation.

S34

Design, development and evaluation of holographic masks for proximity lithography with EUV radiation

Valerie Deuter, Maciej Grochowicz, Sascha Brose, Jan Biller, Detlev Grützmacher, and Larissa Juschkin

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Traditional lithography relies on high-quality optics to project the mask image onto the wafer. Fabrication of such optical projection systems for the EUV lithography is much more challenging task. A promising approach to avoid complex projection optics and to allow for printing arbitrary (non-periodic) structures is the holography. Taking advantage of modern algorithms for iterative designing of synthetic holograms, the described idea enables creating a dedicated optical structure that can be applied for proximity lithography with EUV radiation. The goal is to find a pattern and to fabricate respective holographic mask for Fresnel assisted proximity lithography, which results in the desired intensity distribution on the photoresist coated wafer. We propose to use a hologram (an attenuating phase shifting mask) consisting of arbitrary structures of two-phase levels. For the feasibility study, to simplify the fabrication process, e-beam resist is used as a phase shifting medium, so no structure transfer is required. The hologram has been designed for a wavelength of 13.5 nm with a pixel size of 50 nm. The design and fabrication process of the holographic mask and experimental results of its characterization are presented and discussed. The hologram's imaging performance is evaluated using EUV exposures at synchrotron and with a laboratory plasma-based source.

Presenting Author

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

S35

Calibrated Broadband Spectroscopy using Transmission Gratings in the EUV to DUV Wavelengths

Muharrem Bayraktar[1], Bert Bastiaens[2], 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

Broadband monitoring of EUV lithography light source plasmas is relevant for several purposes including estimating the optics heat load, background scatter and DUV/EUV ratio. We have previously demonstrated that spectroscopy in the EUV and DUV ranges can be conveniently performed using a transmission grating spectrometer from the same viewport without breaking the vacuum. Here, we present the calibration of the transmission grating spectrometer in the EUV and DUV ranges. For these wavelengths, gratings with 10.000 lines/mm and 1.000 lines/mm line densities have been calibrated in the 5.5-41 nm and 40-400 nm wavelength ranges, respectively. The measured diffraction efficiencies have been fitted to a grating model based on rigorous coupled wave approach to reconstruct the grating parameters such as the layer thicknesses and structure widths. These grating parameters can in turn be used to calculate polarization dependence for a calibrated spectroscopy in the aforementioned broad wavelength range.

Presenting Author

Muharrem Bayraktar earned his BSc degree from Bilkent University in 2007, MSc degree from Sabanci University in 2010 and PhD degree from University of Twente in 2015. His MSc research was on digital holography and interference techniques, and applications of these techniques in three dimensional imaging and metrology. His PhD research included development of spectral filters and novel adaptive optical components based on piezoelectric thin films for applications in Extreme Ultraviolet (EUV) wavelengths. His postdoctoral research at the University of Twente is on broadband spectroscopy and imaging for characterization of EUV light sources with funds awarded by NanoNextNL Programme and TKI-HTSM.

S36

Towards High-Resolution Imaging at 13.5 nm using a Fiber Laser Driven High-order Harmonic Source

Wilhelm Eschen[1,2], Getnet K. Tadesse[1,2], Robert Klas[1,2], Herbert Gross[2], Jens Limpert[1,2,3], JanRothhardt[1,2,3]

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In this contribution, we will review our latest results on table-top Coherent Diffractive Imaging using a high-order harmonic source using18 nm wavelength and show our first advances towards high-resolution table-top CDI at 13.5 nm. In contrast to previous work [1, 2] at this wavelength, we employ power-scalable fiber-laser technology, which promises highest performance [3] and shortest acquisition times. In a proof-of-principle experiment at 18 nm, we demonstrate the first reliable resolution test with a Siemens-Star test pattern on a table-top system. The smallest resolved features are only 47 nm in size, see Fig 1 (a)). To reach a wavelength of 13.5 nm our fiber laser system was upgraded for shorter pulse durations (< 10 fs), which enables a photon flux of $>3\times10^9$ photons/s/ 1%BW at 13.5 nm (92 eV). The high spatial coherence (visibility of ~0.9) of the XUV beam is characterized by a double slit which was placed in the focus of the XUV-beam (Fig 1(b) and Fig 1(c)) and shows that our source is suitable for coherent imaging. We will present first imaging results of our imaging system, which, by design, can achieve sub-20 nm resolution. In a next step, the investigation of real-world samples (as e.g. lithography masks in reflection) will be achieved.

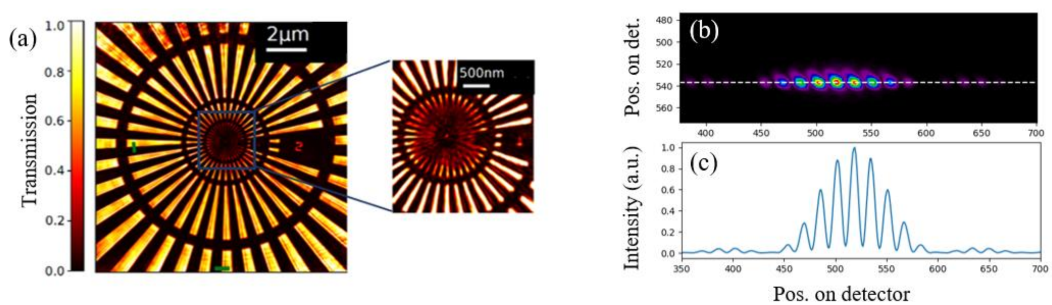

Fig. 1 (a) Imaged resolution test chart with a wavelength of 18 nm. (b) Measured diffraction pattern of the 92 eV beam focused on a double slit. (c) Lineout of the diffraction pattern shown in (b).

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Presenting Author

Wilhelm Eschen is a Ph.D. student at the Institute of Applied Physics in Jena. He is a member of Jan Rothhardts "X-Ray Spectroscopy and Microscopy" group which focuses on the development and application of high photon flux XUV and soft X-ray sources using high average power femtosecond fiber lasers. Wilhelm works on table-top coherent diffractive imaging at 90 eV.

Bio.docx

S37

Plasma-induced Blister Formation and Deuterium Retention in EUV Mirrors

Shih-Chi Wang, Wim Arnold Bik and Thomas Morgan

DIFFER, Eindhoven, The Netherlands

Recent research work [1, 2] shows that blister formation could occur to EUV (Extreme Ultraviolet) mirrors exposed to high-flux hydrogen ions and radicals. It results from hydrogen atoms trapped in the materials and could lead to delamination of thin films [2]. To study the influence of Sn on blister formation, we measured the deuterium retention in Ru-capped samples using Elastic Recoil Detection (ERD) after treatment of a low-temperature (T_e<1 eV) deuterium plasma in a tin-rich environment. The samples were kept close to room temperature during plasma exposures and the plasma parameters were acquired using a Langmuir probe. We found a correlation between blister formation and the amount of Sn on the sample surface. This shows Sn on the surface accelerates deuterium uptake of the Ru-capped target.

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Presenting Author

The author is a PhD student at DIFFER. He works on plasma-surface interactions in relation to vacuum ultraviolet mirrors in a harsh environment such as an extreme ultraviolet lithography tool or a nuclear fusion reactor.

S38

Thin Films Behaving Badly

Görsel Yetik, Cristina Sfiligoj, Victor Vollema, Jan Verhoeven, Joost Frenken

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Thin metallic films are of great importance in a wide variety of practical applications. We investigate the growth and evolution of thin Mo and Ru films, sputter-deposited on Si(100) substrates with a native oxide. In this work, we use a combination of scanning electron microscopy (SEM) and atomic force microscopy (AFM) for imaging and detailed measurements of the surface topography (roughness) plus energy-dispersive x-ray spectroscopy (EDX) and x-ray photoelectron spectroscopy (XPS) for elemental and chemical characterization. The structures that we observe after deposition, reflect the polycrystalline nature of even the thinnest films. In our study of the thermal stability of the films, we focus on grooving of grain boundaries and, at sufficiently high temperatures, on dewetting and other degradation mechanisms.

Presenting Author

Görsel Yetik obtained his BSc degree in physics and engineering from the Hacettepe University in Ankara, Turkey, and his MSc degree in physics from the Technical University of Munich, Germany. Currently, he works as a PhD student in the Advanced Research Center for Nanolithography (ARCNL), in Amsterdam, as a member of the Nanolayers group, headed by Joost Frenken. Yetik's research focuses on the growth and evolution of ultrathin films and their thermal stability.

S39

Edwards Contribution to future EUV Lithography scaling

Jos Donders*, Anthony Keen**, Mohamed Noorani*, Niall Walsh*, Amedeo Bellunato*, Rene Heijink*, David Engerran**

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The approaching introduction of Extreme Ultraviolet Lithography (EUVL) into high-volume manufacturing (HVM) requires appropriate readiness of all supporting infrastructure with specific attention to the demanding availability and throughput targets required to achieve cost effective production.

Edwards has been deeply involved in Advanced Lithography applications and more in particular with EUV Lithography since the early development phase. The transition from 193nm to 13.5nm light requires the EUVL process to be carried out under vacuum, and the demands on the EUV tool development have been significant in order to achieve this, but there is also a consequential impact to the supporting equipment which is maintaining the process environment specifically from the perspective of delivering not only sufficient tool availability[1] but also for other demanding requirements for the vacuum and exhaust gas management sub system

In this paper we discuss the scaling factors that have been taken into account in the design of an integrated vacuum and exhaust gas management sub-system that contributes to meet the targets required to enable EUV Lithography transitioning into High Volume Manufacturing.

Considerations such as safety, gas flows and temperatures to support the necessary operating vacuum conditions as well as reliability, footprint, design flexibility, utility, total energy and availability aspects to support a cost effective overall EUV infrastructure concept will be discussed in this paper.

In the mean-time Edwards have shipped over hundred dedicated, multi-generational, EUV Zenith sub-systems in the last ten years to support the EUVL market and EUV tool platform generations. Using the lessons learned out of this large installed base has been the major process to drive continuous improvement of the system performance.

We will discuss the transition of the requirements from a multi capable light source[2] concept infrastructure (Discharge Produced Plasma and Laser Produced Plasma sources) to support the proof of concept of EUV Lithography into a more dedicated concept to support a High Volume Manufacturing environment as well as the expected future requirements to ensure the EUV Lithography process will become a fully accepted solution for multiple layers into the next most advanced technology nodes for logic and memory applications. Technologies and requirements for potential future light source applications will be reviewed.

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Presenting Author

Jos Donders is the Director of the Edwards Lithography & Patterning sector. In this role he is responsible for the Lithography market and business development strategy in the Edwards Semiconductor Division driving the specific needs for the semiconductor lithography market sector into vacuum and exhaust gas management roadmap requirements as well as playing a lead role in the organizational development of this sector in the Edwards organization globally. After his BSc in Analytical Chemistry in Eindhoven, The Netherlands he gained experience of over 30 years in the industry. Starting his career as a technical process engineer at Philips before joining Edwards where he held various sales, business development and marketing positions for different vacuum related industries and more in particular for the semiconductor industry.

S40

XUV Coherence Tomography (XCT)

Julius Reinhard[1,2], Silvio Fuchs[1,2], Martin Wünsche[1,2], Jan Nathanael[1,2], Johann Jakob Abel[1], Felix Wiesner[1], Slawomir Skruszewicz[1], Christian Rödel[1,2], Gerhard G. Paulus[1,2]

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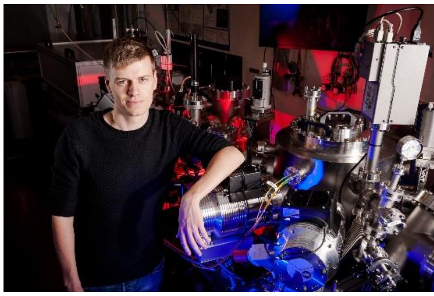
Here we report on a novel 3D imaging method called XCT, which utilizes a broadband high-harmonic generation (HHG) light source to generate high depth resolutions down to 16nm in the silicon transmission window (30eV-100eV). It is based on the principle of Optical Coherence Tomography (OCT). The axial resolution is determined by the coherence length of the light and therefore only dependent on the bandwidth of the source. Tomographic information can be obtained by scanning a small focus over the sample. First experiments were realized at synchrotron radiation sources before the setup was transferred to a laboratory HHG source.

Furthermore a 1D phase retrieval algorithm was developed, which mitigates the intrinsic artifacts of XCT and offers additional spectroscopic information. This information can be used to not only identify the depth of buried layers but also their material.

Another way to mitigate the artifacts is to place a thin membrane as reference a few hundred nanometers in front of the examined sample. While this is technically quite demanding, it enables amplitude splitting XUV interferometry. XCT allows non-destructive measurement of 3D semiconductor samples. It is especially suited to investigate layered structures like mirror coatings, semiconductor devices.

Presenting Author

Julius Reinhard is a PhD Student in the "Nonlinear Optics" group at the University Jena. He received his Master degree in physics in 2018 working on XUV microscopy with a Schwarzschild-Objective. Currently his focus is on developing a laser induced plasma source to transfer XCT to higher energies and possibly combine it with other microscopy methods.



S41

The CompactLight Design Study Project (Invited Presentation)

Gerardo D'Auria

Elettra

CompactLight (XLS) is an International Collaboration of 24 partners and 5 third parties, funded by the European Union through the Horizon 2020 Research and Innovation Programme. The main goal of the project, which started in January 2018 with a duration of 36 months, is the design of an hard X-ray FEL facility beyond today’s state of the art, using the latest concepts for bright electron photo-injectors, high-gradient accelerating structures, and innovative short-period undulators. Compared to existing facilities, the proposed facility will benefit from a lower electron beam energy and will be significantly more compact. It will also have lower electrical power demand as well as lower construction and running costs. An overview of the project and recent achievements are presented.

Presenting Author

S42

Development to Realize the EUV-FEL High-power Light-source for Future Lithography (Invited Presentation)

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

High Energy Accelerator Research organization (KEK)

It is important to develop the high power EUV light source up to or more than 1 kW to realize the 3nm node and beyond. To this end, our group has designed an energy recovery linac (ERL)-based free electron laser (FEL). About the real demonstration of the accelerator technologies, one of the key technologies is a production of high beam quality with small emittance on a high bunch charge. In KEK, there is an ERL test facility. The beam development of the high bunch charge condition has been done and got a reasonable beam quality. Another important milestone should be a real demonstration of ERL-based FEL light production, even though the wavelength is not EUV wavelength as presented at the previous Source Workshop. Last fiscal year, KEK started to contribute another project to develop high average power mid-infrared FEL based on "new laser technology development for processing laser" from NEDO. This FEL can be regarded to become a Proof-Of-Concept machine for the EUV-FEL. At the Workshop, the present status of the POC project and also the achieved beam quality will be presented.

Presenting Author

Hiroshi Kawata obtained in 1982 his doctorate at the Tokyo Institute of Technology in the study of the surface state on the ferroelectric using X-ray diffraction method. In 1982, he became an assistant to Toyama University. In 1983 he moved to the Photon Factory in KEK and contributed to the research by X-ray diffraction, absorption and inelastic scattering based on synchrotron radiation. He became an associate professor in 1992 and a professor in 2000 in KEK. From 2006, he became a project leader of KEK's future light source ERL (Energy Recovery Linac) project and since 2014 he has contributed to the development of EUV-FEL light source design work using ERL accelerator tech, belonging to the Center for Applied Superconducting Accelerator in KEK.

S43

Storage Ring EUV Light Source Based on Steady-state Microbunching Mechanism

Xiujie Deng

Tsinghua University, Beijing, China (On behalf of the SSMB Collaboration)

An initial task force has been established in Tsinghua University collaborating with institutes from China, Germany and the USA to design an electron storage ring for kW EUV radiation generation based on the steady-state microbunching (SSMB) mechanism. In this talk, the basic idea of SSMB as well as the potential advantages of applying it for EUV lithography are briefly reviewed. The main tasks of the collaboration at this moment, which consist of proving the SSMB work principle, the dedicated EUV SSMB lattice design, the effort to address related technical challenges, are then presented with emphasis on the recent important progress about the proof-of-principle experiment conducted at the Metrology Light Source (MLS) in Berlin.

Presenting Author

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

S51

Lensless Imaging with Coherent Extreme-ultraviolet Radiation (Invited Presentation)

Stefan Witte

Advanced Research Center for Nanolithography and Vrije Universiteit Amsterdam

Computational imaging is an elegant approach to microscopy, in which the image formation is achieved using computer algorithms rather than optical components. This approach is particularly interesting for wavelengths at which imaging optics are challenging to manufacture, such as the extreme ultraviolet (EUV) and soft-X-ray spectral ranges, as it allows imaging even without using lenses.

Combined with the coherent radiation from a high-harmonic generation (HHG) source, such lensless imaging methods enable the development of high-resolution EUV microscopes that can be used to image nanostructures in great detail. I will present our work on the development of spectrally resolved lensless EUV imaging. Furthermore, I will discuss the use of lensless imaging methods to characterize HHG beams themselves, turning such imaging tools into a means to study the physics of HHG.

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.

S52

From mW-scale HHG Sources to Extreme-ultraviolet Frequency Combs (Invited Presentation)

Christoph Heyl

DESY

Extreme ultraviolet (XUV) laser sources based on High-order harmonic generation (HHG) are nowadays used for a variety of applications reaching from attosecond physics over XUV imaging to frequency comb spectroscopy. While properties like spatial and temporal coherence, pulse duration and spectral coverage offer unique opportunities, a main limitation of these sources is their rather low power, especially for photon-hungry imaging applications or frequency comb spectroscopy, where only a very small fraction of the generated power can be used. Recent advances in the field have pushed HHG-based XUV sources into the mW average power regime. We will discuss these advances and give a brief outlook into further power scaling possibilities employing high-power fiber laser technology to drive HHG-based XUV sources in single-pass and intra-cavity configurations.

Presenting Author

Christoph received his PhD in 2014 in attosecond physics at Lund University, Sweden (Anne L'Huillier) and University of Marburg (Ulrich Höfer). From 2014-2015 he was a Postdoc in nonlinear optics at Lund University (Anne L'Huillier). From 2016-2017 he was a Postdoc in frequency comb development at JILA, Boulder, US (Jun Ye). Since 2017 he is a Young investigator group leader at Helmholtz-Institute Jena and DESY

S53

High Harmonics of Visible Lasers (Invited Presentation)

Ofer Kfir

University of Göttingen

High harmonics of visible lasers offer a source of extreme-UV (EUV) and X-rays with laser-like qualities, such as high spatial coherence and ultrashort pulses. However, the polarization state of high harmonics was essentially limited to linear, which prevented experimental access to the role of photon-spin in harmonic generation, and hindered the use of high harmonic radiation for chiro-optical investigation with magnetic and other chiral matter.

My talk will follow the path that circularly polarized high harmonics followed in the past few years, from their inexistence, through the first demonstrations [1,2], and the current state of the art [3]. In the first part, I describe the dynamical symmetries that impose polarization constraints on the interaction of light and matter, both at the level of a single atom and of an ensemble. The second part focuses on application of high harmonics for lensless magnetic-imaging, which is especially demanding in terms of the photon-flux and polarization control – two traditional challenges of HHG. I will show quantitative mapping of magnetic domains, which surpass results from large facilities (e.g. synchrotrons) in both space and time: Spatially, by reaching image resolution below the wavelength on a large field-of-view, and temporally, by observing 200 femtosecond dynamics of the magnetic patterns. In the future, accessibility to a new spatio-temporal scales may reveal new dynamical phenomena, and allow for a better understanding of ultrafast magnetism.

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Presenting Author

Ofer received his Bachelor degree from Technion Israel Institute of Technology in Material-Sciences and physics. He received his Ph.D. from the Technion Israel Institute of Technology, on circularly polarized high harmonics, which included a long project in the University of Colorado, Boulder. He is currently a Marie Curie Fellow in the group of Claus Ropers in the University of Göttingen, working on dichroic EUV imaging with HHG, and coherent light-electron interactions.

S54

Progress in Development of kW-class Picosecond Thin-disk Laser Systems for High-power EUV Sources (Invited Presentation)

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

HiLASE Centre, Institute of Physics CAS
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High-average-power sub-picosecond solid-state lasers have become an important tool for hi-tech scientific and industrial applications. In the field of EUV radiation sources, for example, mJ ps pulses generated at high repetition rate serve as a tool for construction of efficient laser-produced plasma-based photon sources at wavelength of 13.5-nm for lithography. High-energy picosecond laser-based Compton X-ray source can be also a compact substitute of large synchrotrons.

Hilase centre in Dolni Brezany (Czechia) focuses on development of such advanced diode-pumped solid state laser technology based on thin-disk architecture and covering spectral range from UV (206-nm) to mid-infrared (4-um), with special emphasize on kW-class sources emitting at 1030 nm (so called Perla platform). Recently, first industrial prototypes based on the Perla platform have been demonstrated. The industrial systems can be tailored upon customer's needs. Alternatively, beam time of the lasers can be provided at Hilase labs.

In this talk we present latest status of high repetition rate regenerative amplifier Perla C delivering 1.6 ps long pulses with pulse energy up to 10 mJ, high energy burst-mode operated multipass amplifier system Perla B, and cryogenically-cooled system Perla A operated at pulse energy of 1-Joule.

Presenting Author

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

S55

Ultrafast Thin-Disk Amplifiers (Invited Presentation)

Thomas Metzger

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With an inexorable demand for increased average and peak power at the same time, the management of heat deposition and the buildup of nonlinearities have become pressingly challenging for energetic ultrafast lasers. Due to its efficient one-dimensional heat removal and the small longitudinal extension of the gain medium, the thin-disk geometry offers exceptional scaling performance both in terms of energy and average power. As a regenerative amplifier, 200 mJ were in fact recently extracted at 5 kHz out of two Yb:YAG disks [1]. A similar amplifier is currently built at TRUMPF Scientific Lasers to demonstrate nonlinear pulse compression to pulse durations <50fs at nearly 2kW, 20kHz and 1kW, 5kHz respectively. Likewise, multipass arrangements have led to >1.5 kW with good temporal and spatial performances [3].

In this contribution, we present different commercial ultrafast solutions based on regenerative amplifiers with up to 200 mJ. Further nonlinear pulse compression experiments such as gas filled multipass cells [4] are in preparation and the current status of the developments will be shown. Thus, combining both technologies, the completion of high-energy sub-50 fs lasers with multi-kW average output powers would be at our fingertips. Such laser sources could give rise to a manifold of exciting applications such as inverse Compton scattering [5], pumping optical parametric amplifiers [6], laser based lightning rod [7], high harmonic [8] and X-ray [9] generation and laser wakefield accelerator-based light sources [10].

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Presenting Author

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

S56

Towards High Harmonic Generation in Laser-Produced Tin Plasma

Jan Mathijssen, Amelie Schulte, Kjeld Eikema, Stefan Witte

ARCNL

Next-generation nanolithography devices use extreme ultraviolet (EUV) radiation, produced by a laser-produced plasma (LPP) in tin. The EUV emission characteristics of this LPP depend strongly on the plasma properties. Therefore, we aim to investigate the spatial and temporal distribution of the different charge states in the tin plasma plume. For this purpose, we are developing a pump-probe experiment in which high harmonics (HH) are generated in a LPP and afterwards analysed in a spectrometer. The HH spectrum is strongly dependent on the plasma properties, as the local charge state composition and electron density influence the phase-matching properties and can lead to resonant enhancement at specific frequencies. Thus, by analysing the HH spectrum, information about the plasma properties can be obtained. The plasma will be generated by sending a 100 ps laser at 1064 nm wavelength, with pulse energies up to 100 mJ on a solid target. The HH will then be generated by amplified laser pulses with a pulse length of 200 fs, a central wavelength of 1550 nm and a pulse energy of 8 mJ. These HH will be characterised with a home-built spectrometer.

Presenting Author

Jan Mathijssen studied Physics and astronomy at the University of Amsterdam. He obtained his BSc in 2016 and graduated for his MSc in 2018. Currently, Jan is a PhD student in the EUV Generation and Imaging group of ARCNL under supervision of Dr. Stefan Witte and Prof. Dr. Kjeld Eikema. His PhD research focusses on the development of an optical parametric chirped pulse amplifier producing ultrashort pulses at 1550 nm and setting up a new experiment to probe laser produced tin plasmas using high harmonic generation.

S57

High-flux XUV Beam-lines Driven by Fiber-based Few-cycle Laser sources

Steffen Hädrich[1], Nico Walther[1], Maxim Tschernajew[1], Fabian Stutzki[1], Marco Kienel[1], Florian Just[1], Sven Breitkopf[1,*], Tino Eidam[1] and Jens Limpert[1,2,3,4]

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2. *Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller-Universität Jena, Albert-Einstein-Str. 15, 07745 Jena, Germany*
3. *Helmholtz-Institute Jena, Fröbelstieg 3, 07743 Jena, Germany*
4. *Fraunhofer Institute for Applied Optics and Precision Engineering, Albert-Einstein-Str. 7, 07745 Jena, Germany*

Coherent XUV sources with unprecedented photon flux levels have recently become available by rapid developments in high average power ultrashort pulse fiber lasers. These sources are an important building block for the next generation imaging systems, which are e.g. required for inspection of wafers written with ever smaller structure. We will present and discuss the current status of high photon flux EUV sources and their potential to being used in 90eV applications. Beyond that scaling strategies of laser power and therewith the photon flux in the XUV by orders of magnitude are presented. Active Fiber Systems is currently developing a carrier-envelope-phase (CEP) stable fiber-based chirped-pulse amplification (FCPA) laser system delivering 5mJ pulse energy at 100kHz pulse repetition rate (i.e. 500W of average power) and with pulse durations of 6fs – a world-record set of laser parameters. Such a system is highly suitable to enable record breaking levels of EUV photon flux, which has the potential to trigger many new and exciting applications in this particular spectral range.

Presenting Author

Sven Breitkopf is the sales director of Active Fiber Systems GmbH in Jena, Germany. He received the Diploma degree in general physics and the Ph.D. degree from the Friedrich- Schiller-Universität Jena, Jena, Germany, in 2011 and 2018, respectively. From April 2018 to April of 2019 he was a project manager at Active Fiber Systems GmbH before being promoted to coordinate the global sales activities. His research interest was focused on high average power ultrafast fiber lasers, enhancement cavities and coherent pulse combining techniques.

S58

Divergence Control of High-harmonic Generation Enables High-brightness extreme-ultraviolet sources

Sylvianne Roscam Abbing, Filippo Campi, Faegheh Sajjadian, Peter M. Kraus

Advanced Research Center for Nanolithography (ARCNL), Amsterdam, The Netherlands

High-harmonic generation (HHG) is a technique that enables broadband, ultrafast, and highly coherent extreme ultraviolet sources. However, the conversion efficiency of the process is low, but all applications of HHG require high-brightness sources. In addition, the HHG pulses have a double-Gaussian beam profile that gives rise to chromatic aberrations, which are rooted in the quantum-mechanical nature of the generation mechanism. By using both 800 nm and 400 nm femtosecond pulses for the generation process, we can manipulate the attosecond electron dynamics of the HHG process, which impacts the phase front of the generated pulses. We have shown by an extensive parameter study that the relative polarization, the ratio between and the phase of the two fields can be used to improve the beam profile by suppressing the tails of the spatial profile, while increasing the overall conversion efficiency. Our result pave the way towards high-brightness HHG sources with improved beam profiles.

Presenting Author

S61

Light source Development for Mask and Wafer Inspection HVM Tools (Invited Presentation)

Reza Abhari

ETH Zurich, Switzerland

ETH Zurich has been developing a droplet based laser produced plasma (LPP) light over the last 12 years, initially focused on the needs of actinic mask inspection while later expanding to other inspection applications. Here, latest technical improvements in the brightness and operational capability of the LPP light source will be presented. Having demonstrated EUV brightness measurements of over 350 W/mm2 Sr, the extendible light source would fulfill all the technical requirements of mask and wafer inspection systems for the present and many future nodes, lowering technology risks for future upgrades. Long run-time testing results will be presented and challenges discussed. The small footprint of the source as well as state of the art platform damping technology ensures that the light source can be seamlessly integrated into the inspection tool. Future plans for light source research and development will also be presented.

Presenting Author

Reza Abhari is Prof. of Energy Technologies at ETH Zurich as well as the Founder of Adlyte AG, a global developer of light sources based in Switzerland. His research areas include; laser produced plasma science, instrumentation and mechatronics, system modeling, and large scale computing including artificial intelligence. He is the author/co-author of over 300 scientific articles and journal publications. He is a member of the Swiss National Academy of Engineering Sciences, a Fellow of ASME, a Christensen Fellow of St Catherine's College, Oxford University, as well as the recipient of many scientific awards. He received his PhD from MIT in Aeronautics and Astronautics and his MA/BA from Oxford University in engineering.

S62

Characterization of discharge based plasmas in the spectral range of 20 - 50 nm (Invited Presentation)

Klaus Bergmann[1], Jochen Vieker[1], Florian Melsheimer[2]

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Discharge based XUV sources are used for various applications in the development of EUV lithography at a central wavelength of 13.5 nm. The emission at a longer wavelength could be of interest for new metrology applications. Discharge based sources will offer an attractive solution because of being compact and easy to operate. In this paper first results of the emission in the range of 20 – 50 nm of a discharge source for different gases will be presented, where the base layout of the source is optimized for the emission around 13.5 nm. Considerations on optimized circuit layout, achievable conversions efficiencies and average power for future systems will be presented.

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 with main focus on XUV source development.

S63

Ultra-clean High-brightness LPP EUV and VUV Source with Rotating-target for Metrology Applications (Invited Presentation)

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

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The report presents further studies of a new high-brightness LPP light source emitting in the EUV and VUV ranges with a fast-rotating liquid metal target. The concept source is based on the usage of unique droplet mitigation techniques: high speed rotating liquid metal target and replaceable carbon nanotubes membrane. Additional protection from ions and fast neutrals is provided by gas flow and magnetic field. The source operates with a high conversion efficiency due to the use of tin as plasma fuel. Fiber IPG 30 W laser provided CE of 1%/2π sr in band 13.5±0.135 nm and 1%/2π in full band 80–120 nm. The brightness of the source in these ranges was 60 W/mm^{2}sr and 22 W/mm^{2}sr respectively at pulse repetition rate 60 kHz. Estimated rate of droplets deposition on a EUV mirror behind the carbon nanotubes membrane was 5 % for 7 weeks (24/7 operating mode). We haven't detected any traces of ion deposition. Sensitivity of the measurements gives an estimate of lifetime lost due to ion deposition 5 % for longer than 80 operation hours. At present, a new generation of the source, designed to operate with a 400 W Nd-YAG laser, is preparing for testing.

Presenting Author

S64

Performance Improvement of Laser-assisted and Laser-driven EUV Sources for Metrology Applications (Invited Presentation)

Yusuke Teramoto[1], Bárbara Santos[1], Guido Mertens[1], Margarete Kops[1], Ralf Kops[1], Wilko van Nunspeet[1], Klaus Bergmann[2]

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The Laser-assisted discharge-produced (LDP) plasma EUV source is developed as a light source for actinic mask inspection. Since the focused laser irradiation is used to ignite the discharge, the LDP plasma has a unique feature of high brightness and high power. A LDP source is currently used in the beam line facility at the customer site of which rated power is 70 W/2□sr and high availability is maintained. The LDP source technology is being further developed as a light source for actinic mask inspection tool. Current focus is to increase the source brightness maintaining stability and reliability. Multiple experiments were performed at the brightness level of between 100 and 150 W/mm^2/sr to study and improve short- and long-term brightness stability. To support HVM and further extendibility, frequency was increased up to 11 kHz to understand the behavior of the components of which the source consists. Brightness was increased to 230 W/mm^2/sr level under which stable, long-term operation was confirmed. In addition to LDP source, the laser-driven source is being researched aiming at the compact high-brightness radiation source. A liquid Sn-covered disk is used as a target and the laser irradiation intensity is adjusted to emit radiation at 13.5 nm. In the previous experiments, we investigated how laser parameter, especially pulse duration, influenced the source brightness. It made us select the appropriate laser. This year, as part of further development, operating frequency was increased to 28 kHz and brightness of 140 W/mm^2/sr was obtained. Long-term tests and design of next-generation source are currently pursued. At the workshop, the latest performance and finding of both source technologies will be presented and discussed.

Presenting Author

Yusuke Teramoto received Ph.D. degree in 2002 from Kumamoto University, Japan. He joined Ushio Inc., Japan in April 2002 and started research and development of Xe- and Sn-fueled discharge EUV sources. In 2008, he moved to Aachen, Germany to participate the co-development program between Ushio, XTREME, Philips and Fraunhofer ILT. He engaged in source development for NXE3100 scanner, especially in power scaling. Now he is working for BLV Licht- und Vakuumtechnik GmbH, an Ushio group company. He is currently the leader of R&D Unit 1 of EUV Business Project managed by Ushio Inc. and working on EUV and X-Ray metrology sources research and development.

S65

Advances in Laser-heated Discharge Plasma: Increased EUV Emission and Change in Plasma Parameters

Florian Melsheimer[1,2,3,4], Detlev Grützmacher[1,4,5], Larissa Juschkin[1]

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[2] RWTH Aachen University, Templergraben 55, 52056 Aachen, Germany
[3] Fraunhofer Institute for Laser Technology, Steinbachstraße 15, 52074 Aachen, Germany
[4] JARA-FIT, Forschungszentrum Jülich GmbH and RWTH Aachen University, Germany
[5] Forschungszentrum Jülich GmbH, JARA-Institute for Green-IT, Peter Grünberg Institute -10, 52425 Jülich, Germany

A laser heated gas discharge plasma source is developed and influence of the laser pulse on plasma properties and emission characteristics is analyzed. The source consists of a hollow cathode triggered gas discharge EUV source with a custom precision trigger and a pulsed CO_2 TEA laser at 10.6 µm for additional heating of the magnetically self-compressed plasma pinch. An increase of emitted EUV power up to 400% and prolonged pulse duration is found.

The laser-plasma interaction of different gasses is explored and the change in transient plasma temperature and density is analyzed with a composition sensitive analysis method from observed spectra. We retrieve the change in shape of the laser heated pinch via a 3-dimensional tomographic reconstruction method and gain access to otherwise inaccessible information. The determined plasma parameters are utilized in a FdTd-simulation for additional insight which is crucial for future hybrid source development.

Presenting Author

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

S68

The Effect of Gas Admixture on the Operation of a Discharge based EUV-Source

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

Gas discharge based EUV sources offer easy implementation and operation in laboratory setups. They are used in the environment of EUV lithography development for metrology and irradiation experiments. A major aspect of source development is to increase the usable output power amongst one maintenance interval. The FS5440 EUV source of Fraunhofer-ILT has a rated in-band emission of 40 W/2πsr around 13.5 nm. It has been studied regarding the effects of gas admixtures on the EUV emission, where the additives are expected to reduce the impact of the hot plasma on the electrodes with respect to sputtering. Beneficial effects of the admixture of Helium to the Xenon operation gas on the conversion efficiency and source stability have been observed. The presented results highlight the effects on the total and spatial distribution of the 13.5 nm emission from the Xenon pinch plasma.

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 and their applications.

S69

Modelling of Laser-triggered Hollow-electrode Capillary -discharge as a Coherent EUV Source at 13.38nm Wavelength

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The soft X-ray laser may be considered as an alternative EUV actinic metrology source with much lower emission power than a conventional incoherent source due to much higher spectral contrast. One of appropriate medium for such lasing is a capillary discharge-produced plasma of nitrogen with collisional recombination pumped 3p-2s, 3s-2p, 3d-2p transitions in H-like ions, emitting at 13.38nm wavelength.
We have chosen the modelling configuration corresponding to an experimental setup with nitrogen filled alumina capillary of 100mm long with pulsed power supply providing the electric current of 60kA amplitude with 30ns rise time. The electrodes made of CuW composite have technological holes along the axis. These holes are required for radiation passage and diagnostics as well as for discharge triggering using hollow cathode effect. To make a discharge channel and pinching more compact (to reduce a contact of hot plasma with capillary wall and its ablation) and more straight (for lasing guiding expected) a picosecond 6mJ Nd:YAG laser beam may be applied along the axis at discharge triggering.
To explore the physical effects, discharge dynamics and to obtain plasma parameters as well as to optimize the experimental setup, the radiation-magneto hydrodynamic code Z* is used. The estimation of possible inversion in nitrogen ion level population in non-equilibrium transient discharge plasma is post processed by means of the atomic code Fly/Flychk.

When pulsed power circuit is switched-on and pulse voltage is applied to electrodes with nitrogen filled capillary between them, the discharge is triggered due to hollow cathode effect as a spark along the axis of the capillary, a tight ionized channel forms. If the laser triggering was applied to preheat the gas, the channel is tighter and its ionization degree is higher. With discharge current rise, the plasma in the channel is heated up through joule dissipation, its pressure increase and the plasma expends. When plasma is heated up over tens electron-volts of temperature, it radiates intensely and ionizes the rest gas in the capillary. The rising current is intercepted by this surrounding plasma and mainly by the plasma near the inner capillary wall. The plasma continues to be heated up through joule dissipation in whole volume. If the initial gas density is low enough the Ampere’s force $j \times B$ overcomes the thermal pressure and pinching starts volumetrically. At some time-moment, around the current maximum (depending on initial gas pressure) the first pinching forms. During pinching, due to plasma compression by magnetic and inertial forces mainly the plasma electron temperature reaches a sharp maximum of 140-150eV (depending on initial gas pressure) near the capillary axis. If the laser triggering was applied the maximum electron temperature is higher by ~20eV. In the pinch, the nitrogen is ionized until NVI-NVIII. The plasma in the pinch is slightly inhomogeneous along the axis (z-direction). That pinching configuration exist during ~7ns, then plasma expands and is cooling down till ~70eV of temperature during 17-21ns. The plasma recombines, during this recombination the inversion between energy levels n=3 and n=2 of H-like nitrogen may appear. The recombining plasma radiates through photorecombination, in lines and through bremsstrahlung, it loses of 4-5J, significant part of its energy. Current decreases, but the Ampere's force overcomes the thermal pressure again, and in ~27ns after the first pinching the second pinch appears with lower temperature of 90-100eV. The decay of the second pinch to ~50eV of temperature takes place during ~17-23ns. The transient plasma recombines during all this time between pinches and after them, and under certain conditions the inversion between energy levels n=3 and n=2 of H-like nitrogen may be obtained.

For the given pulsed power generator parameters, various coupling of capillary with forming line and capillary dimensions with corresponding initial gas pressures (to obtain an effective electric energy transfer to the discharge) were examined. In capillary of 5mm diameter and 0.5-1mb gas pressure, the inversion between energy levels n=3 and n=2 was not obtained. In capillary of 3.2mm diameter and 4-5 m gas pressure, the inversion was obtained, but the lasing gain was not high enough to be observed. In capillary of 2mm diameter and 20-30mb gas pressure, the second pinching is relatively week, nevertheless the inversion of energy levels n=3-2 and H-like ions fraction estimated are high enough to obtain a bright laser burst at 13.38nm wavelength from plasma column of 100mm long.

Presenting Author

Alexandr Jancarek obtained Ph.D. in physics and mathematics from the Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering in 2001. He was a research scientist, lecturer and is assistant professor at the Department of Physical Electronics of CTU. During this time he focused on laser applications and experimental studies with XUV sources, especially driven by capillary discharge.

S70

Table-Top Water-Window Microscope Using Z-pinching Capillary Discharge Source

T. Parkman[1], M. Nevrkla[2], M. F. Nawaz[3], A. Jancarek[2], D. Panek[1], J. Turnova[1], M. Vrbova[1]

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We present a design of a compact transmission water-window microscope based on nitrogen plasma induced by the Z-pinching capillary discharge, operating at wavelength λ = 2.88 nm [1]. The source was built in-house [2], plasma is generated by a current discharge through alumina capillary filled with nitrogen gas. A ceramic capacitor bank is a pulse charged by a Marx-Fitch generator and switched by self-breakdown spark-gap. Average photons flux is 5.5 x 10^{13} photons/(sr x line x pulse), and the plasma spot has a circular shape with diameter 360 μm at FWHM.

The spectrum of soft X-ray radiation produced by the source is filtered by a titanium filter to achieve monochromatic radiation with wavelength λ = 2.88 nm. Filtered radiation is focused by an ellipsoidal nickel-coated condenser mirror [3]. We used a Fresnel zone plate to create an image of a sample transmission on an SXR-sensitive CCD camera. To assess the resolution of the microscope, we imaged a standard sample – copper mesh. The achieved spatial resolution is below 100 nm at half-pitch. The images of Chrysodidymus cells are presented as well as the description of the sample preparation process.

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Presenting Author

Tomas Parkman is a Ph.D. student of Faculty of Biomedical Engineering, Department of Natural Sciences at Czech Technical University in Prague. His main domains are soft x-ray sources and SXR microscopy.

S71

Drop Deformation and Splashing upon Impact: Drop dynamics in the EUV source (Invited Presentation)

Hanneke Gelderblom[1,3], Marise V. Gielen[2,3], Alexander L. Klein[2,3], Sten A. Reijers[3], Rielle de Ruiter[2], Robin B.J. Koldeweij[3], Henri Lhuissier[4], Emmanuel Villermaux[4], Dmitry Kurilovich[5], Oscar Versolato[5], Jacco H. Snoeijer[3], and Detlef Lohse[3]

[1] Fluids & Flows, Department of Applied Physics, Eindhoven University of Technology, The Netherlands,
[2] ASML Netherlands B.V.,
[3] Physics of Fluids, Faculty of Science & Technology, University of Twente, The Netherlands,

The impact of a laser pulse onto a liquid drop can lead to a violent response: plasma formation and local boiling induce a strong propulsion and deformation of the drop and eventually rupture the liquid into tiny pieces. When drops impact onto a solid surface, similar deformation and fragmentation occurs. Hot liquid metal drops impacting a cold substrate in addition freeze upon contact, which strongly alters the drop dynamics. I will discuss the fundamental physics behind these phenomena and their application in industrial plasma sources used for extreme ultraviolet nanolithography.

Presenting Author

Hanneke Gelderblom obtained her PhD degree in Physics of Fluids at the University of Twente (2013). From 2013-2018, she was project leader of the Industrial Partnership Program `Fundamental fluid dynamics challenges in extreme ultraviolet lithography', collaboration between the University of Twente, ASML and NWO. In 2015, she was visiting researcher at Ecole Polytechnique (Paris). Since 2018 Hanneke is Assistant Professor in the Fluids and Flows group in the Department of Applied Physics at Eindhoven University of Technology. Her main research interests are capillary ow phenomena, droplet dynamics, laser-liquid interaction, biofluids and evaporation driven self-assembly.

S72

Thickness Profile of a Stretched, Transparent Sheet of Liquid Metal Formed by Laser-prepulse Impact

Bo Liu[1,2], Dmitry Kurilovich[3], Hanneke Gelderblom[4] and Oscar O. Versolato[1]

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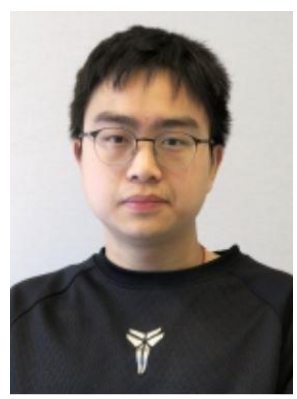
[4] *Department of Applied Physics, Eindhoven University of Technology, Den Dolech 2, 5600 MB, Eindhoven, Netherlands.*

The thickness profiles are measured of expanding sheets of liquid tin as formed by the impact of a nanosecond-pulsed Nd:YAG laser on a microdroplet. Profiles are captured in detail over a wide range of laser-pulse energies and for two droplet sizes using two complementary methods. All obtained thickness profiles are shown to collapse onto a single self-similar curve that enables the prediction of thickness profiles and their time evolution over a wide range of experimental parameters. Surprisingly, upon integration of these profiles, we find that less than half the initial amount of tin remains in the sheet under relevant conditions. Further theoretical analysis indicates that the majority of the mass lost from the sheet ends up as fine fragment sprays. Such possibly detrimental mass loss could be minimized by producing the sheet targets on the shortest possible timescale using more energetic laser prepulses. These findings are valuable for developments in extreme ultraviolet lithography.

Presenting Author



Bo Liu is a PhD student at Advanced Research Center for Nanolithography (ARCNL), also at Department of Physics and Astronomy, and LaserLaB, Vrije Universiteit Amsterdam. He has been working on the experiments of tin micro-droplet responding to the prepulse, in terms of the droplet deformation, the volume distribution of the tin in the target, and the final fragmentation of the droplet.

He received his B.S. from Harbin Institute of Technology, China, majored in Mechanical Engineering. he further obtained his MSc in Mechanical Engineering from Delft University of Technology, the Netherlands. In the second year of my master, I did my internship and the master thesis named *Numerical simulation of oblique droplet impact onto a liquid pool* at ASML, supervised by Dr. Henneke Gelderblom. After his master, he accepted the opportunity of a PhD candidate at ARCNL, with Dr. Oscar Versolato.

S73

In-situ Cryogenic Cleaning Techniques for Tin-contaminated EUV Mirrors

Norbert Böwering[1,2], Christian Meier[1]

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EUV optics of tin-based plasma light sources requires periodic cleaning. The lifetime of EUV collection mirrors is limited considerably by contamination with thick tin deposits that cannot be removed sufficiently fast by plasma etching. We are developing efficient in-situ cleaning techniques for cooled mirror substrates by examining the conditions for droplet splat self-peeling, tin-pest induced transformation and delamination by contraction strain. We study the temperature dependence of the sticking and the phase transformation of tin drops dripped in vacuum onto different unstructured and grating-structured silicon-wafer and multilayer-coated mirror samples with up to 6 inches in diameter. During substrate cooling to temperatures below -30 °C, initially adhesive deposits are fully converted in-situ to brittle gray tin in less than 24 hours. After removal of the detached tin pieces, reflection analysis of EUV multilayer mirrors shows a reduction by only 0.5% at a wavelength of 13.5 nm. This structure-conversion technique is compared with a cleaning method based on substrate cooling to temperatures near -120 °C to induce the delamination of thick tin deposits. These in-situ tin cleaning techniques yield results comparable to ex-situ schemes tested for delamination by optics immersion in liquid nitrogen and deposit removal by CO_2 snowflake aerosol impact.

Presenting Author

Norbert Böwering graduated with a diploma in physics in 1981 in Germany and a Ph. D. in physics from the University of Texas at Austin in 1985. He was a research associate, lecturer and assistant professor at Bielefeld University where he completed the habilitation in 1991. During this time he focused on experimental studies with laser and photoelectron spectroscopies, as well as electron scattering and surface techniques. He also did applied physics work with laser plasmas and EUV multilayer optics. From 2000 to 2017 he has worked in industry on developments of discharge and laser-produced EUV light sources, related metrologies and EUV collector mirrors during several employments, mainly a Cymer and ASML. Now he carries out nanomaterial and technology developments with applications to EUV light sources and optics cleaning as an independent consultant and private research professor at Bielefeld University.

S74

Playing with the Temporal-shape of a High-power Nanosecond 1064 nm Laser pulse to Explore EUV Generation and Different Droplet-deformation Regimes

Zeudi MAZZOTTA

Advanced Research Center for Nanolithography (ARCNL)

The generation of Extreme-Ultra-Violet (EUV) light is a key component enabling nanolithography with nanometer resolution. The efficiency of the EUV generation process depends, in good part, on the primary tool used in the EUV source: a high-intensity laser ($> 10^{11}\ W/cm^2$) illuminating a liquid tin target. The impact creates hot plasma emitting EUV light. Different laser pulse parameters, such as duration, energy, fluence and wavelength, affect the EUV light characteristics, an important one being the spectral purity (the ratio between usable EUV light and the full plasma-generated spectrum), and induce different target deformations. In the particular case of tin droplets, the capability of "playing" with the temporal shape of our nanosecond $1064\ \mathrm{nm}$ pulses opens a fan of several deformation regimes, where the behaviour of the droplet after laser impact changes significantly. Our laser pulse durations span from $0.43\ \mathrm{ns}$ to even $1.1\ \mu\mathrm{s}$. We can shape a flat top temporal profile as well as a pulse train, where each pulse can be *separately* tuned, allowing deformation and yield studies also with pre-pulses. This makes our table top laser unique in its kind, with its $0.6\ \mathrm{GW}$ peak power and $44\ \mathrm{W}$ average power.

Presenting Author

Zeudi is a postdoctoral researcher at the Advance Research Center for NanoLithography (ARCNL), part of the EUV generation and imaging group, in Amsterdam, since January 2019.
Born in the south of Italy, Zeudi developed her love for logic and science since she was a child, until she decided to continue at the university with either physics or mathematics. The choice was not simple, but her love for rigours led her defend after three years, in February 2010, her bachelor thesis in mathematics at Universitá del Salento. But physics was always on her mind, therefore she wanted to merge the two paths in her master degree. She found in Milano what she was looking for: Mathematics applied to Physics. She defended her Master theses in April 2013 at the University of Milano, on robust optimization algorithms.
While attending some classes in particle physics, driven by curiosity, she learned about the AEgIS experiment at CERN: a project studying the neutral antimatter freefall in the earth gravitational field. This made her choose to apply for a PhD position in Milano. She got the position, and from January 2014 she worked both in the AEgIS experiment at CERN and in the Quantum Laboratory of Milano. Here, she got close to lasers and wrote her thesis about how to efficiently excite a positronium cloud by using lasers and nonlinear crystals, and how the thermal spread of an atomic cloud can be addressed to achieve an efficient excitation. In Milano, she also worked on a project related to Quantum Coherence Tomography, where she studied the effects of

dispersion on two-photon interference.
In the last months of PhD work she got in contact with a group of people working in Pisa, Italy, at ILIL (Laboratorio Irraggiamento Laser Intensi), to help them building the last amplification stage of their TW class laser system.
After defending her PhD thesis in January 2017, she temporary worked at CERN for one month and then in March 2017 she went to Paris, where she worked for 3 months at the Laboratoire Aimé Cotton on Rydberg atoms and, in June 2017, she won a Postdoc position at the LULI laboratory for the EuPRAXIA project. Here she worked on the conceptual design of a PW class laser system for laser-plasma acceleration till January 2019, when she started a new postdoc position at ARCNL, where she currently works on the source lasers for EUV generation.

S75

Observation of the Whole Thomson Scattering Spectrum for Diagnostics of EUV and Soft X-ray Light Source Plasmas

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Laser Thomson scattering (LTS) technique is well known as a powerful diagnostic tool to reveal spatial distributions and temporal evolutions of electron density (n_e), electron temperature (T_e), ion temperature (T_i), and averaged ionic charge (Z) of various types of plasmas[1]. We have applied LTS to laser-produced tin plasmas for High-power EUV light sources. When visible light is used as a probing laser, Thomson scattering from the EUV light source plasma is in the collective regime. In this regime, LTS spectra consist of ion and electron components. We measured ion component of the LTS spectra. Obtained 2D-profiles of n_e and T_e enabled direct comparisons between the plasma parameters and EUV emissivity[2]. Now, we have tried to diagnose soft X-ray light sources for water-window imaging (2.4-4.4 nm) and Beyond EUV (6.x nm). However, to measure n_e, T_e and Z of these plasmas, the ion component of the LTS spectrum is not sufficient. Simultaneous detections of the ion and electron components are necessary. Then, we have fabricated customized spectrometers to detect the two components.

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Presenting Author

Kentaro Tomita is an Assistant Professor at the Kyushu Univ. He 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.

S76

Research of Tin-droplet Generation, Diagnosis and Synchronization with Laser

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Based on fluid dynamics theory of jet breakup, theoretically the production process of tin droplets was simulated by the use of Ansys Fluent software. Experimentally A droplet tin target generator was developed to generate tin droplets that were continuously ejected downwards. Based on the LabVIEW virtual instrument, a droplet online monitoring system was built to evaluate the performance of the droplet tin target generator, and a diameter of 180 μm was obtained. Stable spray tin droplets with a frequency of 20 kHz. Based on the stable sprayed tin droplets, a spatio-temporal synchronization system of pulsed laser and droplet interaction is constructed, which can continuously and accurately focus the laser pulse to a single tin droplet and solve the pulse laser and droplet tin target time and space. The key technical issues of synchronization lay an important foundation for the research of laser plasma dynamics.

Presenting Author

Wang Xinbing is the presenting author for this annual workshop. He is a professor at Huazhong University of Science & Technology, Wuhan, China. His main research is laser produced tin-droplet plasma EUV source.

S77

Ion energy distributions from laser-produced tin plasmas

Lucas Poirier, Diko Hemminga, John Sheil, Ronnie Hoekstra, Wim Ubachs,
Oscar Versolato

ARCNL

Next-generation nanolithography machines will employ extreme ultraviolet (EUV) light to enable patterning of nanometer-scale features relevant to semiconductor manufacturing. The source of EUV light (13.5 ± 0.27 nm) will be the emission from highly charged tin ions in a hot, dense laser-produced plasma. Although these plasmas are key to EUV photon generation, their expansion into the environment in front of the droplet can lead to contamination of the main collection mirror in nanolithography machines. Therefore it is necessary to gain insight into the tin ion energy distributions to explore a possible mitigation strategy.

In the present work, we have undertaken a theoretical and experimental study of the ion energy distributions from plasmas produced by Nd:YAG laser pulses on tin microdroplets. We have employed Faraday cups to characterize the angular distribution of ion emission. In addition, an electrostatic analyzer (ESA) has been utilized to provide charge-state resolved ion kinetic energy spectra. The plasma expansion from the tin droplet is simulated with RALEF-2D, a two-dimensional radiation-hydrodynamics code. The kinetic energy spectrum of the expanding plasma can be compared with its experimental counterpart. With this combination of methods we aim to provide a better understanding of the expansion of laser-produced tin plasmas.

Presenting Author

Lucas Poirier got a master's degree in Physics at l'*Ecole Normale Superieure* in Cachan, France. He then moved to Amsterdam, the Netherlands to explore the use of inorganic perovskite nanocrystals in photovoltaics and LED research. However, he recently started a PhD degree in the Advanced Research Center for Nanolithography in Amsterdam, focusing on experimental aspects of the tin plasma expansion in a vacuum.

S81

Fundamental Structure and Interaction Quantities of Ionic Tin Quantities

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Lucas Poirier[1], Subam Rai[1,2], Joris Scheers[1,3], Ruben Schupp[1,3], John Sheil[1], Diko Hemminga[1,3],
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In this talk our research progress on resolving the structure and radiation properties of multiply charged tin ions and characterizing their interactions with stopping gas and plasma-facing materials surrounding a laser-produced plasma (LPP) extreme ultraviolet (EUV) light source is summarized.
The following topics will be addressed:

- EUV line identifications in Sn^{13+}, Sn^{14+}, and Sn^{15+} ions using a new method (CRESpR) to reconstruct charge state resolved spectra from an electron beam ion trap (EBIT).
- The strong contribution of excited-to-excited state transitions to the generation of 13.5-nm EUV light in Sn LPP EUV sources.
- Optical depth as a single, pertinent scaling-law parameter capturing the overall trends in the observed changes in the complex EUV emission of the Sn LPP plasma.
- The absence of single-scattering events in keV Sn ion scattering on transition metals as Mo and Ru. According to the commonly used SRIM simulation package these single-scattering events should dominate.
- The measurement of charge exchange cross sections for ions traversing H_2 gas, by means of the production of molecular hydrogen ions and protons.

Presenting Author

S82

Unexpectedly Large Radiative Emission between Highly-excited States in Sn Laser-produced Plasma (Invited Presentation)

J. Colgan[1], A. J. Neukirch[1]
F. Torretti[2], J. Sheil[2], R. Schupp[2], M. M. Basko[3], M. Bayraktar[4], R. A. Meijer[2], S. Witte[2], W. Ubachs[2], R. Hoekstra[2], and O. O. Versolato[2]

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The opacity spectra of Sn plasma in the extreme ultraviolet (EUV) regime are calculated, for local thermodynamic equilibrium conditions, using the Los Alamos suite of atomic codes [1,2] and its opacity and plasma modeling code ATOMIC [3,4]. The detailed atomic structure calculations of the complex Sn ions show an unexpectedly large contribution to EUV emission from transitions between highly-excited states, up to approximately 90% of the total opacity, with the more well-known EUV transitions to the ground manifold contributing only 10% [5]. The transitions between doubly- and triply-excited states are shown to be serendipitously aligned around 13.5 nm, the wavelength of relevance in EUV light sources for the nanolithographic industry. In this presentation, we discuss in detail the atomic structure calculations [1,2] that were necessary to compute the opacity spectra at the conditions (plasma temperature of 32 eV and electron density of 1020 cm□3) found to match the laser-produced-plasma measurements [6]. As well as including large numbers of configurations to fully capture configuration-interaction effects, we found it necessary to add modifications to the `scale factors' in the CATS atomic structure code (based on Cowan's codes [7]), so that accurate transition wavelengths are found for excited-excited transitions, as well as the ground-excited transitions.

Our opacity calculations, in conjunction with a radiation transport model, are validated by the comparison with the emission spectra of a droplet-based, laser- produced Sn-plasma light source [5]. The calculations are in excellent agreement with the measurements and show that a single-temperature, single-density plasma can be used to capture the majority of the emission features.

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This project has received funding from European Research Council (ERC) Starting Grant number 802648 and is part of the VIDI research program with project number 15697, which is financed by the Netherlands Organization for Scientific Research (NWO). Part of this work has been carried out at the Advanced Research Center for Nanolithography (ARCNL), a public-private partnership of the University of Amsterdam (UvA), the Vrije Universiteit Amsterdam (VU), NWO and the semiconductor equipment manufacturer ASML. Work at Los Alamos supported by the ASC PEM Atomic Physics program. Los Alamos National Laboratory is operated by Triad National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy (Contract No. 89233218NCA000001).

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.

S83

XUV Spectroscopy of Strontium Laser Produced Plasmas (Invited Presentation)

T. Miyazaki, G. O'Sullivan and P. Dunne

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

Soft x-ray Spectra, in the range from 1 nm to 13 nm, were recorded from strontium plasmas formed by pulses from 20 ps, 170 ps and 5.5 ns Nd:YAG lasers operating at the fundamental wavelength of 1064 nm. Features due to 3d – 4p and 3d – 4f transitions were identified by comparison with spectra from adjacent ions and atomic structure calculations with both the Cowan code and the Flexible atomic code (FAC). As in the spectra of ions of other elements in the fifth row of the periodic table, resonant $3d^{n}$ – $3d^{n-1}4p^{1}$, $3d^{n}$ – $3d^{n-1}4f^{1}$ and satellite lines $3d^{n-1}4s^{1}$ – $3d^{n-2}4s^{1}4p^{1}$ and $3d^{n-1}4s^{1}$ – $3d^{n-2}4s^{1}4f^{1}$ were observed over the 3.0 nm to 8.5 nm region, emitted by 10^{+} to 19^{+} ions. These Δ = 1 transitions provide a range of narrow band emission features which may match to specific multi-layer combinations for reflective optics in the extreme ultraviolet region of the spectrum.

Presenting Author

S84

Spectroscopic Measurements of Sn Laser-Produced Plasmas

Lars Behnke[1], Zoi Bouza[1], Ruben Schupp[1], Joris Scheers[1,2], Francesco Torretti[1,2], Muharrem Bayraktar[3], Ronnie Hoekstra[1,4], Wim Ubachs[1,2], Oscar Versolato[1]

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Sn and its highly charged ions are of great technological interest, as these are the emitters of extreme ultraviolet light near 13.5 nm in next-generation nanolithographic applications. This radiation conveniently overlaps with the reflectivity of molybdenum-silicon multi-layer mirrors used as projection optics in EUV lithography scanners, thus making Sn an ideal choice of element for nanolithographic purposes. In our experiments, molten Sn micro droplets are dispensed from a droplet generator into a vacuum vessel and are illuminated by high-intensity pulses of an Nd:YAG laser, operating at its fundamental wavelength λ = 1064 nm. We also produce plasma using an Optical Parametric Oscillator operating at longer wavelengths. The spectral emission of the produced plasma was measured using a broadband transmission grating spectrometer. In this work, we present and compare Sn emission spectra produced by the two laser systems mentioned above and through this comparison we gain insight of the effects of the laser wavelength on the emission characteristics of the plasma.

Presenting Author

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

S91

Radiation hydrodynamic simulations of λ = 2 μm irradiation of tin microdroplets and slab targets

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Recently, Langer *et al*. performed a numerical study examining plasma properties (material temperature, average ionization state) that arise from the irradiation of λ = 2 μm laser light on a uniform tin vapour [1]. The authors calculated extreme ultraviolet (EUV) spectra for laser power densities in the range (0.4 – 2.9) x 10^{11} W/cm^2 and provided conversion efficiencies for this parameter space. Inspired by this study, we have undertaken radiation hydrodynamic simulations, using the RALEF-2D code [2, 3], of λ = 2 μm laser irradiation on a tin microdroplet and slab target. Time–dependent electron densities and plasma temperature profiles will be presented for various laser illumination parameters. We identify, using both analytic and numerical means, the laser parameters which yield optimal plasma conditions (electron temperature, electron/ion densities) enabling intense EUV emission and high conversion efficiencies.

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Presenting Author

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

S92

Radiation Hydrodynamic Simulation on EUV light from 2μm Laser-irradiated Tin Droplet (Invited Presentation)

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

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In order to simulate the benchmarking test problems of extreme ultra-violet (EUV) emission from a tin droplet irradiated by the 2μm wavelength laser light, we carried out radiation hydrodynamic simulations using STAR2D code in the cylindrical geometry. This code treats one fluid two-temperature model, solving the conservative Euler system equations for conserved variables such as density, momentum, and total energy density (ρ, $\rho\mathbf{u}$, ρe_t) and the non-conservative equations of ion and electron temperatures (T_i, T_e) with the realistic equation of state (EOS). The radiation spectrum divided into 40 unevenly spaced groups is solved by the flux-limited diffusion model, using emissivity and opacity data calculated based on the collisional radiative steady state (CRSS) and the local thermal equilibrium (LTE) atomic models [1]. So far, we have confirmed the verification and reliability of our code for the various conditions with 1.06 μm and 10.6 μm laser wavelengths, showing that the emitted radiation spectrum and the conversion efficiency (CE) from the laser to 1% bandwidth at 13.5nm can be reasonably simulated. Especially one of our important results is the prediction that 10.6 μm wavelength laser irradiation on tin droplet plasmas could give relatively high CE above 6% with the double-pulse scheme [2]. In this workshop, we would like to present our simulation results and discuss about the benchmarking problem for the 2μm laser wavelength.

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Presenting Author

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

S93

On the Optimal Choice of the Wavelength of Laser Radiation for LPP EUV Sources (Invited Presentation)

V.V. Ivanov[1,2], V.M. Krivtsun[1,2], V.V. Medvedev[1,2], and K.N. Koshelev[1,2]

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We examine theoretically the efficiency of EUV generation by laser-produced plasma as a function of the wavelength of laser radiation. The radiation hydrodynamics code RZLINE is used to model the relevant physical processes during the interaction of high-radiance laser radiation with a condensed-matter target. In the numerical experiment, we consider bulk Sn target exposed to pulsed laser radiation. The wavelength of laser radiation is varied from 1 μm to 10 μm. We consider two different configurations resulting in a) high-power EUV generation and b) high-brightness EUV generation. Outlook for mass-limited targets is also discussed.

Presenting Author

S94

Simulations of EUV Sources Driven by CO_2 and Thulium Lasers (Invited Presentation)

Steven Langer, Emily Link, Tom Galvin, Howard Scott, and Craig Siders

Lawrence Livermore National Laboratory

Current EUVL sources are driven by CO_2 lasers, but the high electrical power consumed by the lasers is an issue. Could another type of laser reduce power consumption and still have high 13.5 nm conversion efficiency? Future generations of ICs will have smaller features. Can an EUV source with a shorter wavelength deliver good conversion efficiency and be developed in a timely manner? This talk uses HYDRA computer simulations of targets driven by CO_2 and Thulium lasers to address these and other questions related to EUVL sources. The thulium laser design is adjusted to optimally deliver the desired laser power, pulse shape, and repetition rate.

The combined HYDRA and laser simulations provide estimates of system electrical-to-EUV power efficiency. The key goal of this talk is to show how simulations may be used to speed the development of future EUVL sources.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344 and was supported by the LLNL-LDRD Program under LDRD-17-ERD-033. LLNL-ABS-790340.

Presenting Author

S95

Modelling Radiation from High-Z elements in Tokamak Plasmas and Similarities with X-ray and VUV sources (Invited Presentation)

M G O'Mullane[1], N R Badnell[1] and S S Henderson[2]

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The preferred plasma facing materials in magnetic fusion are now metals for engineering and operational reasons with beryllium and tungsten used for the first wall and liquid lithium and tin in innovative divertor concepts. This has prompted significant atomic physics modelling efforts to address the issues of interest: quantifying visible lines from neutral and lowly ionized ions to measure influx, identifying spectral features in the x-ray and VUV to track impurity accumulation in the core plasma and to provide sufficiently precise coefficients to model the transport and total radiated power of these metals in the plasma.

For tungsten and tin we illustrate the ADAS approach to generating the atomic data needed to calculate a temperature and density dependent ionization balance and self-consistent spectral emission and radiated power. The individual ions have complex atomic structure so optimization techniques for configuration choice and energy level adjustments are guided by a metric of converging total power. The refinements of the fundamental atomic data change the spectral prediction, so validation against the emission from diverse plasmas such as EBIT spectra, tokamak emission and plasma sources are, or will be, required to quantify the overall accuracy of the atomic data and population model.

Presenting Author

Martin O'Mullane has worked in magnetic fusion, firstly as a graduate student at University College Cork on impurity transport, and then joined Prof. Summer's group at the University of Strathclyde working on all aspects of atomic physics related to fusion. Based at Culham he is the director of ADAS, the Atomic Data and Analysis Structure. This comprehensive set of atomic data and codes was developed at JET to underpin the modelling and diagnosis of radiation emitted from magnetically confined fusion plasmas. ADAS is now an international consortium and is used in many fusion laboratories. The OPEN-ADAS website acts as a repository for fundamental atomic data calculations and derived data tailored for finite density plasma modelling.

S96

Radiation and Hydrodynamics Evolution Properties of Laser-produced Plasma

Qi Min [1], Maogen Su [1], Duixiong Sun [1], G. O'Sullivan [2], Chenzhong Dong [1]

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[2] School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

We present a simplified radiation hydrodynamics model based on the fluid dynamic equations and the radiative transfer equation. In this model, we ignore the formation of the plasma plume and the initial plasma shape is assumed as a semi-ellipsoid. Only three numerical parameters are used to describe the initial plasma expansion stage: the initial dimensions, density and initial temperature of the plasma. The initial distributions of plasma temperature and ion density follow Gaussian distributions and the pressure at the plasma boundary is zero.

The outputs of the model consist of the evolution of the electron temperature, atom, and ion density, and the temporal and spatial evolution of various transient particles in plasma, as well as the simulated spectrum related to certain experimental conditions in a specified spectral window. In order to test the model and provide valuable experimental feedback, a series of EUV emission spectra of Sn plasmas have been measured and simulated, as is indicated in Figure 1. It can be seen that good agreement has been obtained in most cases. The results indicate that the setting of the initial and boundary conditions in the model is suitable.

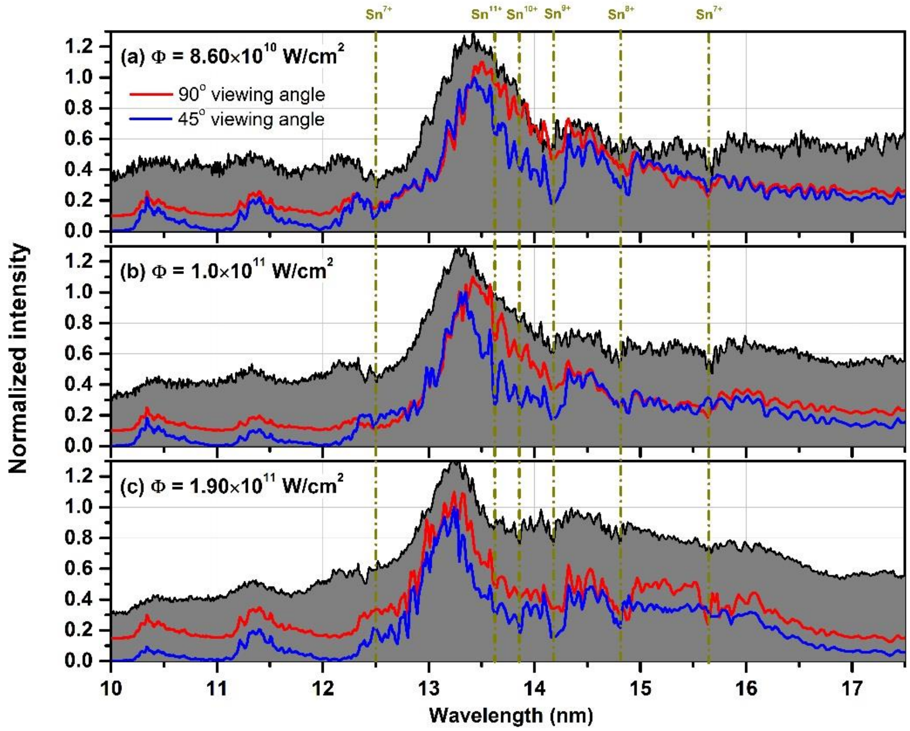


Figure 1. Comparisons of spectral profiles between the experimental and two simulated results based on the radiation hydrodynamics model, in which the black line represents the experimental spectra detected at a 45° viewing angle, and the red and blue lines present the simulated results for 90° and 45° viewing angles, respectively.

Presenting Author

S101

ARCNL: the Advanced Research Center for Nanolithography

Joost Frenken

The Advanced Research Center for Nanolithography (ARCNL)

The Advanced Research Center for Nanolithography (ARCNL) is a public-private partnership between the University of Amsterdam (UvA), the VU University Amsterdam (VU), the Dutch Research Council (NWO) and the semiconductor equipment manufacturer ASML. ARCNL started in 2014 and now has 10 research groups and approximately 90 employees. The research of ARCNL is devoted to the basic physics and chemistry underlying current and future lithography technology, with a strong emphasis on EUV lithography in the context of the semiconductor industry. ARCNL's research program is concentrated in three departments: *Source*, *Metrology* and *Materials.* These will be introduced and illustrated in more detail by the other presentations in this Showcase session.

Presenting Author

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

S102

ARCNL's Metrology Department: New Light on Nanostructures

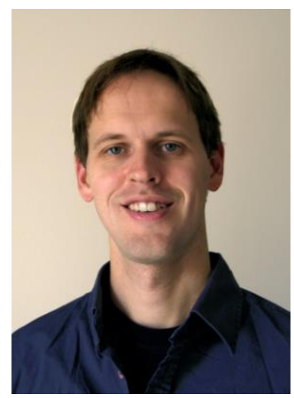
Stefan Witte

The Advanced Research Center for Nanolithography (ARCNL)

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

I will give an overview of the ongoing research in all groups and highlight the various links and application perspectives of the different research topics.

Presenting Author



Stefan Witte received his PhD in 2007 from the Vrije Universiteit Amsterdam, for work on intense ultrafast laser development and precision spectroscopy. He did postdoctoral work at on nonlinear microscopy and biomedical imaging (Vrije Universiteit) and on ultrafast electron dynamics and lensless imaging with high-harmonic sources (JILA, University of Colorado). Since 2014 he is a group leader in the EUV Generation and Imaging group at ARCNL and head of the Metrology Department, and is associated with the Vrije Universiteit Amsterdam as an assistant professor. He was awarded an ERC Starting Grant in 2014. 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.

S103

The Materials Department: A Superficial Research in Depth

Sonia Castellanos

The Advanced Research Center for Nanolithography (ARCNL)

The Materials Department is dedicated to the fundamental understanding of chemical and physical events that surfaces and materials undergo in different locations of the EUV scanner. In this talk, we will give an overview of the research performed by the four groups in this department. We will present the investigations by the *Nanolayers* group on the morphology/composition evolution of thin films relevant for the EUV optics under the scanner operation conditions. Highlights will be shown on the study of mechanisms underpinning friction and wear occurring on the wafer table performed by the *Contact Dynamics* group. At the other side of the wafer, we will explain the findings by the *EUV Photoresists* group regarding EUV-induced chemistry in new photoresists and its correlation with the sensitivity and resolution of the materials. At the epicenter of the department and connecting all its activity, the research of the *Materials and Surface Science for EUV lithography* group on fundamental interactions between surfaces, reactive gases, and EUV light will be outlined. The target of the department is to employ the knowledge developed by each group to propose disruptive innovations to implement on mirrors, pellicle, wafer table, and photoresists in order to improve the lithography process.

Presenting Author

Sonia Castellanos obtained her PhD in Chemistry (extraordinary prize) from the University of Barcelona in 2005. Her thesis was dedicated to the synthesis of organic molecular materials with applications in electronic devices. As a postdoc at the Humboldt Universität zu Berlin, she was awarded with an Alexander von Humboldt fellowship to investigate photoresponsive molecular systems (photoswitches). She then realised a second postdoc at TU Delft to design photoresponsive hybrid porous materials for gas adsorption and catalysis applications.

Since 2016, Castellanos is the leader of the EUV Photoresists group at ARCNL. Her group investigates processes triggered by highly energetic extreme ultraviolet (EUV) photons on tailor-made hybrid materials.

S104

ARCNL's Source Department: Physics of Plasma Sources of EUV Light

Oscar Versolato

The Advanced Research Center for Nanolithography (ARCNL)

The Source Department at ARCNL is dedicated to the fundamental understanding of the physical processes involved in each step in generating extreme ultraviolet (EUV) light. In this talk, I will give an overview of the research performed by two groups in this department. This talk starts with the highlights in the research and development of advanced solid-state laser systems by the *EUV Generation & Imaging* group and their studies of the response of tin droplet plasma to various laser parameters. Subsequently, I will discuss recent progress made in my own group *EUV Plasma Processes* on topics ranging from the fluid dynamics of droplet deformation upon laser-pulse impact to the origins of light generated by a solid-state-laser-driven tin plasma.

Presenting Author

Oscar Versolato received his PhD in 2011 from the University of Groningen, The Netherlands, for work on laser spectroscopy on trapped, short-lived radium ions. He did postdoctoral work at the Max-Planck-Institute für Kernphysik in Heidelberg, Germany, on spectroscopy and sympathetic laser cooling of highly charged ions (with PTB Braunschweig, DE), and molecular ions (with Aarhus University, DK). Since 2015 he is a tenure-track group leader in the EUV Plasma Processes group at the Advanced Research Center for Nanolithography (ARCNL) in Amsterdam. His present research interests include plasma sources of extreme ultraviolet radiation, droplet deformation and fragmentation after laser pulse impact, physics of highly charged ions, and spectroscopy. He was awarded the 2016 NWO Vidi research grant as well as the 2018 ERC Starting grant. He is the head of the Source Department.

S105

High-harmonic generation and EUV science

Peter Kraus

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

Coherent pulses of extreme ultraviolet light by high-harmonic generation (HHG) are becoming valuable tools for extreme-ultraviolet lithography (EUVL). The high brightness and directionality of HHG pulses make HHG interesting for imaging and metrology applications. The femtosecond to attosecond durations of these pulses allow time-revolved investigations of fundamental processes in EUVL.

In this talk, I will outline the ambitions of ARCNL's "High-harmonic generation and EUV Science" group to develop new HHG sources, and to apply those to fundamental ultrafast spectroscopy challenges in EUVL, by presenting two experiments that we recently carried out.

In the first experiment, we constructed a brighter HHG source by combining the driving laser with its orthogonally polarized second harmonic. This source generates a more intense and at the same time less divergent beam, by restricting the available quantum paths that contribute to HHG, while at the same time narrowing the ionization windows within a laser cycle.

In the second experiment, we have used an HHG source to follow the exposure kinetics of a metal-oxo photoresist, reminiscent of the new type of resist materials that are being investigated for EUVL. The exposure kinetics allow to follow and determine the quantum efficiencies of resists at extreme-ultraviolet wavelengths.

Presenting Author

Peter Kraus obtained his PhD at ETH Zurich (Switzerland) in 2015. He developed and advanced the techniques of high harmonic-spectroscopy for investigations of electronic and nuclear structure and dynamics of molecular systems. Peter subsequently worked at the University of California, Berkeley (USA) on the development of new experimental techniques for investigating attosecond phenomena in solid-state materials. He started as a tenure-track group leader/assistant professor at ARCNL in May 2018. Peter is leading a program to develop extreme ultraviolet (EUV) sources from high-harmonic generation and apply them for ultrafast spectroscopy and nanoscale metrology experiments with relevance to nanolithography.

S106

Improving Optical Overlay Metrology Using Computational Imaging

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Semiconductor manufacturers continue to increase the component densities on computer chips by reducing the device dimensions to less than 10 nm. This trend requires faster, more precise and more robust optical metrology tools that contain complex and high-precision optics with challenging imaging requirements. Metrology tools with the above settings will introduce lens aberrations to the system meaning that aberration compensation will be needed. In our group, we explore dark-field Digital Holographic Microscopy (df-DHM) as a potential technique to meet the above requirements at acceptable complexity of the optics. With df-DHM we measure the complex field of a chip on a camera which allows the use of computational techniques to correct for residual imperfections that would give rise to metrology errors. With the reconstructed image of the target we can measure parameters like overlay (pattern placement) with sub-nm precision.

In this presentation, we will explain this technique along with the benefits compared to other known techniques and we will address the main challenges than we need to surpass for the next generation of optical metrology tools. We will present the first holographically obtained images of metrology targets with our custom-built df-DHM and we will identify the next steps of our investigation.

Presenting Author

Christos Messinis is a PhD employee at Advanced Research Center for Nanolithography (ARCNL) on the group of Computational Imaging under the supervision of Prof.dr. Arie den Boef. The main goal of his research is the development of a metrology tool based on holography, capable of robust semiconductor metrology on a large wavelength range (400-900 nm) with sub-nm precision. Christos holds a BSc on Material Science and a MSc on Photonics-Lasers both obtained from the University of Patras, Greece.

S107

A DC Injector for a Compact Free Electron Laser

Tom Lucas

The Advanced Research Center for Nanolithography (ARCNL)

Free electron lasers (FELs) are capable of delivering extremely high intensity hard X-rays with an unprecedented brilliance. The compact light project is a concept design study which investigates the use of state-of-the-art 12 GHz RF accelerating structures to reduce the overall cost and length of such facilities. Our work has focused on the design of a DC photo-injector. This DC injector aims to offer a highly reliable and robust solution which is also cost effective. This makes it more feasible that individual institutions may be able to build and operate such a facility.

Presenting Author

Thomas Lucas is a postdoctoral fellow employed by ARCNL and working at Eindhoven University of Technology (TU/e). He began at TU/e this year after completing his PhD at CERN through the University of Melbourne where his thesis topic was "the phenomenology of high gradient accelerating structure for the compact linear collider". Thomas position at TU/e involves the development of a compact high gradient injector for future free electron lasers and Compton sources.

S108

Interactions of Multiply Charged Fast Tin Ions with Solid Targets and Neutral Gases

S. Rai[1, 2], M.J. Deuzeman[1, 2], O.G. Tjepkema[1], W. Noordam[1], S. A. Koeleman[1], O.O. Versolato[1] and R. Hoekstra[1, 2]

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Multiply charged tin ions expelled from laser produced tin plasma have kinetic energies as high as tens of keV[1]. At the ZERNIKELEIF facility, Zernike Institute for Advanced Materials, the University of Groningen, charge state, energy and isotope-selected beams of tin ions can be produced by the 14 GHz supernanogan ECRIS and transported to setups dedicated for specific ion studies.

At the Surface Physics setup, a series of experiments is being performed to study the backscattering of tin ions from plasma facing materials like molybdenum and ruthenium solid targets. The current focus is to understand the observed discrepancy between experimental results and the predictions of SRIM [2], a standard package widely used to simulate ion-solid interactions, the prime discrepancy being the absence of the single-scattering peak in the experimental energy spectra.

At the CHEOPS setup of the facility, pulsed ion beam enters the collision chamber where it crosses neutral H_2 gas jet target. The species (molecular hydrogen ions and protons) produced as a result of ion-H_2 collisions are identified by means of Time of Flight mass spectrometry. In this way channel specific charge exchange cross sections of tin ions colliding with hydrogen gas can be determined.

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Presenting Author

Subam Rai is a Ph.D. researcher in the EUV Plasma Processes group at the Advanced Research Center for Nanolithography (ARCNL), Amsterdam. He performs his research at the Zernike Institute of Advanced Materials (ZIAM), University of Groningen, the Netherlands. Before starting his Ph.D. research, he obtained a master's degree in Physics from the Sri Sathya Sai Institute of Higher Learning, India and worked as an intern at the Raman Research Institute, India. His current research activities are focused on the characterization and physical understanding of the interactions of energetic ions with plasma-facing surfaces and neutral gases.

S109

The Transition from Short to Long Timescale Pre-pulses: Laser-pulse Impact on Tin Microdroplets

Randy Meijer[1,2], Dmitry Kurilovich[1,2], Oscar O. Versolato[1], Kjeld S.E. Eikema[1,2], Stefan Witte[1,2]

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The interaction of intense laser pulses with micron-sized metallic droplets is a subject of specific importance for the further development of laser-based extreme ultraviolet (EUV) light sources[1]. In a multi-pulse scheme, the droplet is first deformed by a pre-pulse before the impact of a final main pulse generates the EUV emitting plasma from this target. The pre-pulse characteristics have a large impact on e.g. conversion efficiency of laser light into in-band EUV radiation, repetition rate scaling, and generation of liquid tin debris. A detailed understanding of pre-pulse dynamics can therefore be a key factor in advancing source power and efficiency.

Two main pre-pulse deformation regimes have been established: that of sheet expansion by plasma pressure after impact of a 'long' >10 ns pulse described by incompressible flow[2,3], and that of spherical expansion by internal cavitation after impact of a 'short' <100 ps pulse dominated by the presence of shockwaves[4]. In the latter regime the process of spallation can also occur when the shockwave reflects off the opposing surface after propagation through the droplet. In this work we study the transition between these long and short pulse regimes by scanning pulse durations from 0.5 ns to 7.5 ns FWHM, and analysing the obtained target shapes in detail.

Our measurements show that pulses of 0.5 ns duration, although significantly longer than reported before[4], cause deformation primarily dominated by shockwaves, accompanied by a strong spherical expansion. By increasing pulse duration towards 7.5 ns we observe the transition from spherical to flat expansion and the increase of propulsion. We find agreement with a previously identified scaling of propulsion with laser energy impinging on the droplet[3], and also quantify scaling as a function of pulse duration. Furthermore, the use of temporally flat pulses shows a notable scaling of spall velocities with peak intensity. From these results, we gain insight into the balance between compressible and incompressible flow induced by laser impact.

In summary, we find scaling laws for propulsion, expansion, and spall velocities as function of pulse duration and energy. These findings extend our understanding of laser-droplet interaction and enlarge the spectrum of controllable target shapes that can be made available for future EUV sources.

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Presenting Author

Randy Meijer is a PhD researcher in the EUV Generation and Imaging group at the Advanced Research Center for Nanolithography (ARCNL) in Amsterdam The Netherlands. He obtained his master's degree in Physics at the University of Amsterdam with a project on nano-optomechanics and plasmonics at the NWO institute AMOLF. At the start of his PhD research at ARCNL Randy developed an Nd:YAG laser system with arbitrary temporal pulse shaping capabilities. He now uses these advanced shaping capabilities in experiments on laser-droplet interaction, relevant for EUV light sources used in present-day nanolithography machines. His specific focus is on understanding and tuning the deformation of the tin microdroplet after laser impact.

S110

Detection of Hidden Gratings through Multilayer Nanostructures using Light and Sound

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In semiconductor device manufacturing, it is often necessary to optically detect the presence of micro/nano structures buried underneath many dielectric and metallic layers. An example of a buried structure is a so-called alignment grating, which is a grating etched in Si. When light is diffracted off such a grating, a small change in position of the wafer changes the phase difference between the -1st and +1st order diffracted light beams, which can be used to determine the position of the wafer with great accuracy. However, when optically opaque dielectric and metallic layers are deposited on top of these gratings, it becomes very difficult to detect them. Here we demonstrate that we can detect the presence of grating buried under optically opaque metal and dielectric layer using photoacoustics in an ultrafast pump-probe scheme.

We show that this technique works for samples that are similar to the one that’s used in the semiconductor manufacturing industry. We fabricated a sample that partially mimics the materials/structure used in the fabrication of 3D NAND memory. The sample has alternating layers of silicon oxide and silicon nitride between the flat metal layer and the grating. We observe the time-dependent diffracted probe signal from the gratings buried underneath the metal and dielectric layer. We emphasize that the observation of diffraction in itself implies an acoustic grating at top surface of the metal layer, caused by the buried grating. We explain the shape and strength of the time-dependent diffracted signal by understanding the various phenomena that are involved such as, ultrafast electron and phonon dynamics, diffusion of electron energy, propagation of acoustic pulses in matter and diffraction of light from acoustic waves. Our results show that photoacoustics may be a promising technique for the detection of buried gratings in wafer alignment applications.

Presenting Author

Stephen Edward obtained his Master of Science degree in Physics from the National Institute of Science Education and Research, Bhubaneswar, India (2015). During the master's program, he wrote his master's thesis on the generation of CW single-frequency UV radiation in a single resonant optical parametric oscillator. Stephen subsequently moved to Amsterdam to start as a Ph.D. candidate in EUV Target's group at Advance Research Centre for Nanolithography. He carries out experimental works in the fields of photoacoustics metrology and ultrafast dynamics in metals. He developed and advanced optical metrology techniques using laser-induced ultrasonics, for the detection of nanostructures under opaque metals and dielectric.

S111

EUV Spectroscopy of Highly-charged Sn ions in an Electron-beam Ion Trap

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Extreme ultraviolet light used in nanolithographic applications is emitted from a laser-produced Sn plasma. The emission stems from electronic transitions in highly charged tin ions, primarily Sn^{8+} to Sn^{14+}. We present spectroscopy on these type on ions trapped in an electron beam ion trap (EBIT) located at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany. A method is introduced to retrieve charge-state-resolved spectra from the convolved EBIT spectra. Several new lines in 14+ are found, confirming the fine structure splitting of the $4p^5 4d$ configuration previously investigated. Furthermore, line assignments are made of Sn^{15+}, which has received little attention in literature. The strong transitions of this ion are found within the industrially relevant 2% bandwidth around 13.5 nm. The assignments are made using the Cowan code. The obtained level energies are compared to published GRASP calculations and configuration-interaction many-body perturbation theory predictions by the AMBiT code.

Presenting Author

Joris Scheers is a PhD applicant at the Advanced Research Center for Nanolithography in Amsterdam, The Netherlands. His PhD research focusses on spectral investigations of laser-produced Sn plasmas. He studied applied physics at the Eindhoven University of Technology, The Netherlands, with a specialization in plasma physics.

S112

In situ Monitoring the Effect of Corrosion on the Surface Morphology of Crystalline Silicon

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Single crystal silicon is an essential material for the semiconductor industry, extensively used in integrated circuit devices, high-density information storage devices, and dynamic micro-and nanoelectromechanical systems (MEMS and NEMS). Exposure of this material to humid and charged environments can induce corrosion (oxidation) of the surface, leading to changes in surface morphology that can potentially impact eventual device performance.

In this work, we use electrochemical atomic force microscopy (EC-AFM): a technique that combines classical AFM using an unbiased probe together with a three electrodes electrochemical cell, to monitor *in situ* the changes in sample surface morphology as a function of corrosion environment. Both polished and unpolished p-type single crystal (100) silicon wafers were studied; and corrosion rates, corrosion potentials and their relationship with surface morphology evaluated.

Presenting Author

Fiona Elam obtained her Master's degree in chemistry from The University of Edinburgh; a degree programme that included a year-long internship at the SKF Engineering & Research Centre in The Netherlands. Following graduation in June 2011, she joined speciality chemicals company Croda International in England, enrolled on the company's Graduate Training Scheme. In June 2014 she returned to The Netherlands as a PhD student/Marie Curie Fellow at the Dutch Institute for Fundamental Energy Research (DIFFER) and FUJIFILM. Her research focused on controlling porosity in multi-layer silica thin films deposited using plasma enhanced chemical vapour deposition. She defended her PhD thesis in January 2018, and from April 2018 she has been working as a postdoctoral researcher in the Contact Dynamics group at the Advanced Research Center for Nanolithography (ARCNL), in Amsterdam, on the topic of tribochemistry and tribocorrosion in nanolithographic systems.

EUV

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