2010 International Workshop on Extreme Ultraviolet Sources

November 13-15, 2010

University College Dublin ▪ Dublin, Ireland

Abstract Book

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Contents

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Welcome

Dear Colleagues;

I will like to welcome you to the 2010 International Workshop on EUV Sources in Dublin, Ireland.

This new annual workshop will focus on wavelengths of 13.5 nm or less for next generation EUV sources, as well as technology for high-brightness metrology sources at 13.5 nm to support extreme ultraviolet lithography (EUVL). Potential applications of EUV sources in non-EUVL areas also will be discussed. The workshop will include papers on EUVL and soft X-ray sources. Papers on high power EUV sources at 13.5 nm to support commercial EUVL applications will also be presented.

This workshop will provide a forum for researchers in the EUV and soft X-ray areas to present their work and discuss potential applications of their technology. I expect that researchers as well as the end-users of EUV and soft X-ray sources will find this workshop valuable. The workshop proceedings will be published online.

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

Best Regards

Vivek Bakshi
Organizing Chair, 2010 International Workshop on EUV Sources

EUV Source Technical Working Group (TWG)

Reza Abhari (ETH Zurich)
Jinho Ahn (Hanyang University)
Peter Anastasi (Silson)
Sasa Bajt (DESY)
Vadim Banine (ASML)
Klaus Bergmann (XTREME / ILT-Fraunhofer)
Davide Bleiner (University of Bern)
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Francesco Flora (ENEA)
Debbie Gustafson (Energetiq)
Ahmad Hassanein (Purdue University)
Takeshi Higashiguchi (Utsunomia University)
Larissa Juschkin (Aachen Univesity)
Konstantin Koshelev (ISAN)
Rainer Lebert (Bruker)
Peter Loosen (ILT-Fraunhofer)
James Lunney (Trinity College, Dublin)
John Madey (University of Hawaii)
Hakaru Mizoguchi (Gigaphoton)
Patrick Naulleau (LBNL)
Katsunobu Nishihara (Osaka University)
Iwao Nishiyama (SELETE)
Fergal O'Reilly (UCD)
Gerry O'Sullivan (UCD)
Luca Ottaviano (University of L'Aquila)
Yuriy Platonov (RIT)
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Valentino Rigato (INFN-LNL)
Jorge Rocca (University of Colorado)
David Ruzic (Univeristy of Illinois)
Akira Sasaki (JAEA)
Leonid Shmaenok (PhysTex)
Menachem Shoval (Intel)
Emma Sokell (UCD)
Harun Solak (PSI)
Mark Tillack (UC San Diego)
Andrei Yakunin (ASML)
Hironari Yamada (PPL)
Sergey Zakharov (Nano-UV / EPPRA)

Padraig Dunne (UCD) Co-Organizing Chair

Workshop Agenda

Agenda Outline

Saturday, November 13, 2010

Location: Clinton Auditorium, UCD Campus, Building # 30

5:00 - 7:00 PM	Reception and Speaker Prep

Sunday, November 14, 2010

Location: Clinton Auditorium, UCD Campus, Building # 30

EUVL Applications of EUV Sources

8:00 AM	Pickup at the Hotel
9:00 AM – 12:00 PM	Workshop Presentations
12:00 -1:00 PM	Lunch
1:00 – 4:30 PM	Workshop Presentations
4:30 – 6:00 PM	Poster Session and Reception
6:00 PM	Dinner (Guinness Visitor Center)

Monday, November 15, 2010

Location: O'Reilly Hall, UCD Campus, Building # 40

Non-EUVL Applications of EUV Sources

8:00 AM	Pickup at the Hotel
9:00 AM – 12:00 PM	Workshop Presentations
12:00 -1:00 PM	Lunch
1:00 PM	Depart for tour of Newgrange

WORKSHOP AGENDA

2010 International Workshop on EUV Sources

November 13-15, 2010, University College Dublin, Dublin, Ireland

Saturday, November 13, 2010

5:00 – 7:00 PM Reception and Registration

Sunday, November 14, 2010

9:00 AM Session 1: Introductions

Welcome to UCD (Intro-1)
Des Fitzgerald, VP Research, UCD

Introduction - Day 2 (Intro-2)
Vivek Bakshi, EUV Litho, Inc.

9:15 AM Session 2: Keynote-1

Next Generation of EUV Lithography: Challenges and Opportunities (P14)
Vadim Banine, ASML

9:45 AM Session 3: Next Generation HVM Sources

Update: 1st generation Laser-Produced Plasma Source System for HVM EUV Lithography (P4)
Hakaru Mizoguchi, Gigaphoton

New Type of DPP Source for EUVL Based on Liquid Tin Jet Electrodes (P19)
Konstantin Koshelev, ISAN

High Power EUV DPP light Source (P1)
Vladimir Borisov, TRINITI

10:45 AM Break (15 Minutes)

11:00 AM Session 4

Next Generation non 13.5 nm EUV Sources

Towards Shorter Wavelength EUV and Soft X-ray Sources (P45)
Gerry O'Sullivan, UCD

Investigation of Atomic Processes in Laser Produced Plasmas for the Short Wavelength Light Sources (P10)
Akira Sasaki, JAEA

Are the Extremely Hot Oxygen and Nitrogen Plasmas the Debris-less Soft X-ray Light Source? (P27)
Hajime Tanuma, Tokyo Metropolitan University

Experimental Study of Laser Produced gadolinium Plasma Emitting at 6.7 nm (P20)
Konstantin Koshelev, ISAN

Rare-earth Plasma Extreme Ultraviolet Sources at 6.5-6.7 nm for Next Generation Semiconductor Lithography (P6)
Takeshi Higashiguchi, Utsunomiya University

12:40 PM LUNCH (50 Minutes)

1:30 PM Session 5: EUV Sources for EUV Metrology - 1

15 minute Presentations

The Request for High-brilliant XUV Sources: A First Principle Approach (P2)
Rainer Lebert, Bruker

EQ-10 Electrodeless Z-Pinch EUV Source for Metrology Applications (P22)
Debbie Gustafson, Energetiq

Brilliance Scaling of Discharge Based EUV and Soft X-ray Sources (P5)
Klaus Bergman, Xtreme/ ILT

Multiplexed EUV Sources based on a Compact Module with High Irradiance and Low Etendue for Actinic Inspections and Metrology Applications (P34)
Sergey V. Zakharov, NanoUV

Robust Liquid Metal Collector Mirror for EUV and Soft X-ray Plasma Sources (P41)
Ken Fahey, UCD

Characterization of a High Brightness Sn Droplet EUV Source (P3)
Oran Morris, ETHZ

Optimization Studies of the LPP Short-wave Radiation Source with Xe Gas Jet Target in the Ioffe Institute (P11)
Serguei G. Kalmykov, Ioffe Physical-Technical Institute

Advanced INNOSLAB Solid-state-lasers for XUV/EUV-generation (P37)
Peter Loosen, ILT

3:30 PM Break (15 Minutes)

3:45 PM Session 6: ML Optics

Multilayer Optics for EUV and Beyond (P25)
Hagen Pauer, Fraunhofer-Jena

Status of EUVL Multilayer Optics Deposition at RIT (P31)
Yuriy Platonov, RIT

Development of Reflective Coatings for BEUV Lithography (P17)
Denis Glushkov, ASML

Development of Multilayer Spectral Purity Filters for EUVL tools (P29)
Leonid A. Sjmaenok, PhysTex

X-ray Optics for the LCLS Free-electron Laser (P49)
Regina Soufli, LLNL

5:30 – 7:00 PM Session 7: Poster Session

7:00 PM Depart for Dinner (Guinness Visitor Center)

End of Day 2

Session 7: Poster Session

Clinton Auditorium, 5:30 -7:00 PM, November 14, 2010

Topic: Next Generation HVM Sources

1. **Scattering of CO2 Laser Radiation on Tin Plasma Targets** (P26)
V.V. Medvedev, FOM

2. **Understanding the Behavior of Laser-produced Tin Plasmas by Time-Resolved Spectroscopy and Simulation of their Spectra** (P39)
Imam Kambali, UCD

3. **Laser-produced Plasmas of Gold-tin Alloy for EUV sources** (P40)
Imam Kambali, UCD

4. **Tin Target Modelling for 13.5 nm LPP EUV** (P44)
John White, UCD

5. **Optimisation of CO2 Laser-produced Sn Plasmas for Next-generation Semiconductor Lithography Sources** (P51)
Thomas Cummins, UCD

6. **Emission Spectroscopy from Laser-Produced Plasmas of Relevance to Source Development** (P53)
Colm O' Gorman, UCD

7. **Rare-earth Plasmas as Next Generation Extreme Ultraviolet Lithography Sources at 6.5-6.7 nm** (P8)
Takamitsu Otsuka, Utsunomiya University

8. **Modelling of Laser Produced Gadolinium Plasma Source at 6.7 nm** (P18)
V.Novikov, KIAM

Topic: ML Optics

9. **5 sr Collector Mirror Coatings for High Power Laser Produced Plasma EUV Sources** (P23)
Marco Perske, Fraunhofer-Jena

Topic: EUV Sources for Metrology

10. **Computational Optimization of the Gas-jet Target in the LPP Short-wave Radiation Source** (P12)
Serguei G. Kalmykov, Ioffe Physical-Technical Institute

11. **A Study of the Laser Produced Plasma in Stationary Gases at Low Pressures** (P13)
Serguei G. Kalmykov, Ioffe Physical-Technical Institute

12. **Influence of High Energy Electrons on EUV and Soft X-ray Emission Spectra of Nonequilibrium Plasma** (P32)
Vasily S. Zakharov, EPPRA

13. **High Intensity EUV and Soft X-ray Plasma Sources Modelling** (P33)
Sergey V. Zakharov, NanoUV

14. **Time and Space Resolved Optical Plasma Diagnostics of Table-Top Scale Laser Produced Tin Plasmas** (P35)
Colm Fallon, DCU

15. **Time Resolved EUV Emission Spectra of Table-Top Scale Laser Produced Tin Plasmas** (P36)
Patrick Hayden, DCU

16. **High Order Harmonic Radiation from Laser Plasmas** (P38)
Robert Stefanuik, UCD

17. **Z-pinch Discharge in Laser Produced Plasma** (P43)
Isaac Tobin, TCD

18. **Design and Analysis of Liquid Metal EUV Collector Mirrors using the Zemax Ray Tracing Code** (P52)
Ken Fahey, UCD

Topic: EUVL Metrology

19. **EUV Laser Application for Optical Lithography** (P16)
Davide Bleiner, University of Berne

20. **EUV Dark-Field Microscopy for Actinic Defect Inspection** (P48)
Larissa Juschkin, Aachen University

21. **Interference Lithography at 11 nm with a Laboratory Gas Discharge Source** (P46)
Larissa Juschkin, Aachen University

Topic: Non-EUVL Applications of EUV Sources

22. **GIXUVR- Grazing Incidence Extreme Ultraviolet Reflectometry: An All-Optical Technique for Metrology of Ultra-Thin Layers** (P47)
Larissa Juschkin, Aachen University

23. **Metal Impurities in LiF: Opportunity for X-ray Imaging Detectors Development** (P24)
F. Somma, University of Roma Tre

24. **Spectral and Temporal Behaviors of Alkali Metal Vapor Extreme Ultraviolet Sources for Surface Morphology Applications** (P9)
Takeshi Higashiguchi, Utsunomiya University

Monday, November 15, 2010

9:00 AM Session 8: Introduction

Introduction-Day 3 (Intro-3)
Vivek Bakshi, EUV Litho, Inc.

9:05 AM Session 9 : Keynote-2

Liquid-jet Water-window Sources for Nano-scale Imaging (P50)
Hans M Hertz, KTH

9:35 AM Session 10

Non-EUVL Applications of EUV Sources

15 Minute Presentations

Two Colour and Two Photon Ionization Processes in Intense Extreme UV and Optical Laser Fields (P54)
John Costello, DCU

Results Obtained with High Efficiency Gratings for EUV application EUV Interferometer Application, EUV source specifications (P28)
Philippe Michallon, CEA-Leti

Interference Lithography of Graphene Oxide with a Table-top X-ray Laser Source (P42)
Luca Ottaviano, Università dell'Aquila

10:05 AM Break (15 Minutes)

10:20 AM Session 11

EUV Source for EUVL Metrology - 2

15 Minute Presentations

Principles and Utility of the EUV Laser (P15)
Davide Bleiner, University of Berne

Design of a Clean, High Brightness Light Source for EUV Lithography Research in Shorter Wavelength Region (P30)
Kazuyuki Sakaue, Waseda University

10:50 AM Session 12

EUV Sources for Non-EUVL Applications

15 Minute Presentations

EUV / Soft X-ray Development at Energetiq Technology (P21)
Debbie Gustafson, Energetiq

Extreme Ultraviolet Source at 40 nm with Alkali Metal Vapor for Surface Morphology Applications (P7)
Takeshi Higashiguchi, Utsunomiya University

11:20 AM Workshop Summary and Announcements

Workshop Summary and Announcements (Summary)
Vivek Bakshi, EUV Litho, Inc.

12:00 PM Lunch

1:00 PM Workshop Adjourned (Leave for Tour of Newgrange)

Abstracts

P1

High Power EUV DPP Light Source

V.M.Borisov, G.N.Borisova, A.Ju.Vinokhodov, S.V.Zakharov, Ju.B.Kirukhin,
V.A.Mishchenko, A.V.Prokofiev, O.B.Khristoforov

The State Research Center of the Russian Federation Troitsk Institute for Innovation and Fusion Research (SRC RF TRINITI), Troitsk Moscow region, Russia

Discharge produced plasma (DPP) system has been developed as a viable approach for the EUV scanner light source ($\lambda=13.5\pm0.135$ nm). The source is based on a laser-initiated discharge in tin vapor between rotating disk electrodes.

The paper focuses in the first part on the results of the computer simulation of laser-induced discharge with the characteristic of electrical circuit and laser beam which were similar used in the experiment.

In the second part of the paper we describe the experimental results obtained at operation of the source with the input power up to 70 kW. The output EUV power more than 1 kW/2π in the 13.5±0.135 nm spectral band was achieved at repetition frequency 7 kHz.

Presenting Author

P2

The Request for High-brilliant XUV Sources: A First Principle Approach

Rainer Lebert [1], Urs Wiesemann[1], David Schäfer[2], Thomas Wilhein[2], Christoph Phiesel[2], Dominik Esser[3], Marco Hoefer[3], Dieter Hoffmann[3], Klaus Bergmann[3]
Holger Stiel[4]

[1] Bruker Advanced Supercon GmbH
[2] University of Applied Sciences Koblenz; RheinAhrCampus; Institute for X-Optics
[3] Fraunhofer Institute for Laser Technology
[4] Max-Born-Institute

High brightness source is a general requirement for nano-imaging and is linked to resolution, detector size and exposure time. For 10 nm targeted resolution in soft-x-ray microscopy or EUV mask inspection leads to a demand for high-brightness sources with 50-2000 W/mm²/sr for future nanoscopes or mask metrology tools. Medium power discharge sources are a brigde, providing fast access and early learning.

It is shown that sources of < 50 µm diameter are most efficient in investment and CoO. However, no real LPP product source exists for metrology. Moreover, lasers with parameters dedicated to maximize EUV or soft-x-ray brightness are not available from the shelf. With a special laser a LPP high-brightness source of > 100 W/mm²/sr for the water.window soft-x-rays in single line emission has been realized for x-ray microscopy. For being extended to industrial use in EUV technology, a concept for integrating new own developments for highest position stability at up to 100 kHz repetition rate are investigated.

Results from a first proof of concept experiment shows conversion efficiencies of > 1.5 % from laser to inband EUV. With > 25 W laser at up to 10.000 Hz repetition rate, brillances above 100 W/mm²/sr were achieved. With the existing network of competence, full scalability to any brightnes demand < 2000 W/mm²/sr is envisioned.

Presenting Author

P3

Characterization of a High Brightness Sn droplet EUV Source

O. Morris, A. Giovanninni, B. Rollinger, and R. S. Abhari

Swiss Federal Institute of Technology Zurich, Sonneggstrasse 3, 8092 Zurich,
Switzerland

Extreme Ultraviolet Lithography (EUVL) is a leading candidate for the future development of microchips with feature sizes of 32 nm or less. Tin laser-produced plasmas (LPPs) are the most promising source of in-band radiation for EUV lithography and inspection applications. Tin-droplet targets have the ability to supply the minimum mass required to generate EUV radiation, leading to substantial decrease in the amount of generated debris. Metrology applications require a compact laser-plasma source that will generate EUV radiation at minimum cost.

At the Laboratory for Energy Conversion, ETH Zurich we have developed a high brightness, low etendue and high irradiance EUV source. Absolute intensity measurements of the EUV radiation, formed using the droplet target, have been recorded over 2 pi steradian with respect to the plasma. The droplet generator, a fully in-house developed system, was synchronized with a Nd:YAG laser at a frequencies up to 20 kHz.

The EUV detector employed was a calibrated energy monitor, mounted on a custom built robotic arm, enabling the recording of the EUV emission over a full hemispherical region. The spatial profile of the plasma was measured at a range of angles with respect to the plasma. In this paper, the variation of the in-band emission as a function of angular position, relative to the plasma, will be presented and discussed.

Presenting Author

P4

Update: 1st generation Laser-Produced Plasma source system for HVM EUV lithography

Hakaru Mizoguchi[1], Tamotsu Abe, Yukio Watanabe, Takanobu Ishihara, Takeshi Ohta,
Tsukasa Hori, Akihiko Kurosu, Hiroshi Komori, Kouji Kakizaki, Akira Sumitani,
Osamu Wakabayashi[1], Hiroaki Nakarai[1], Junichi fujimoto [1], Akira Endo[2]

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The 1st generation Laser-Produced Plasma source system “ETS” device for EUV lithography is under development. We report latest status of the device which consists of the original concepts (1) CO_2 laser driven Sn plasma, (2) Hybrid CO_2 laser system that is combination of high speed (>100kHz) short pulse oscillator and industrial cw-CO_2, (3) Magnetic mitigation, and (4) Double pulse EUV plasma creation. Maximum burst on time power is 104 W (100 kHz, 1.0 mJ EUV power @ intermediate focus), laser-EUV conversion efficiency is 2.5%, duty cycle is 20% at maximum. Continuous operation time is so far up to an hour.

Presenting Author

P5

Brilliance Scaling of Discharge Based EUV and Soft X-ray Sources

Klaus Bergmann[1], Markus Benk[1], Larissa Juschkin[2], Serhiy Danylyuk[2],
Bernd Nikolaus[3], Jürgen Kleinschmidt[3], Rainer Lebert[4], Urs Wiesemann[4]

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Discharge based EUV sources have experienced a significant progress in the last decade at different places. They are commercially available and are nowadays used in scanners for EUV lithography and related development projects in the semiconductor industry. The technology has been proven to be scalable from 13.5 nm wavelength down to the water window range (2.4 - 4.4 nm), which envisions a new generation of compact systems making use of soft x-ray and EUV light for metrology, patterning or microscopy. For microscopy applications, such as AIMS (Aerial Imaging Microscopy) of EUV masks, a high brilliance is required. This paper gives an overview of the status of currently achievable brilliance values in the EUV and soft x-ray range. Based on the existing data the potential of brilliance scaling is discussed. Results on different applications, i.e., XUV microscopy and interference lithography using discharge sources will be presented. The financial support of the German Research Ministry acknowledged.

Presenting Author

P6

Rare-earth Plasma Extreme Ultraviolet Sources at 6.5–6.7 nm for Next Generation Semiconductor Lithography

Takeshi Higashiguchi[1,2], Takamitsu Otsuka[1], Noboru Yugami[1,2], Deirdre Kilbane[3],
John White[3], Padraig Dunne[3], Gerry O'Sullivan[3], Weihua Jiang[4], and Akira Endo[5]

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Laser-produced dense plasmas have been targeted as high efficiency and high power sources of extreme ultraviolet (EUV) radiation. The development of sources of EUV emission with a wavelength less than 10 nm is a subject of considerable interest. Wavelengths shorter than 10 nm are especially useful for next generation semiconductor lithography, i.e. beyond 13.5-nm [1] and for other applications, such as material science and biological imaging near the water window. In particular, EUV emission at the relevant wavelength may be coupled with a Mo/B_4C multilayer mirror with a reflective coefficient of 40% at 6.5–6.7 nm [2]. We have demonstrated a laser-produced plasma EUV source operating in the 6.5–6.7 nm region based on rare-earth targets of Gd and Tb. The spectra of these resonant lines around 6.7 nm (in-band: 6.7 nm ± 1%) suggest that the in-band emission increases with increased plasma volume by suppressing the plasma hydrodynamic expansion loss at an electron temperature of about 50 eV, resulting in maximized emission [3].

[1] D. T. Attwood, "*Soft X-Rays and Extreme Ultraviolet Radiation*" (Cambridge University Press, Cambridge, 2000), Chap. 6
[2] Fraunhoffer IOF Annual Report 2007
[3] T. Otsuka *et al*., Applied Physics Letters **97**, 111503 (2010)

Presenting Author

P7

Extreme Ultraviolet Source at 40 nm with Alkali Metal Vapor for Surface Morphology Applications.

Takeshi Higashiguchi[1,2], Hiromitsu Terauchi[1], Takamitsu Otsuka[1], Mami Yamaguchi[1], Keisuke Kikuchi[1], Noboru Yugami[1,2], Rebekah D'Arcy[3], Padraig Dunne[3], and Gerry O'Sullivan[3]

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Photon energies between 10 and 100 eV correspond to wavelengths between 12 and 120 nm in the electromagnetic spectrum. These photon energies are high enough to induce photochemical reactions in most materials, including hydrogen, carbon, and oxygen and are very useful for surface material processing. Light sources in the vacuum ultraviolet (VUV) and extreme ultraviolet (XUV) spectral regions will thus be applied in various scientific and engineering fields, such as semiconductor lithography, diagnosis in dense plasmas, materials processing, photochemistry, biological imaging, and so on. A photo-induced desorption spectrometer employing a compact, efficient discharge-produced microplasma XUV source in 20−200 nm broadband spectral region has been proposed, which has the advantage of neither damaging or melting the surface after irradiation [1]. We have built and characterized a discharge-produced potassium plasma extreme ultraviolet source. Potassium ions produce strong broadband emission around 40 nm with a bandwidth of 8 nm [full width at half-maximum (FWHM)]. By comparison with atomic structure calculations, the broadband emission is found to be primarily due to 3*d*–3*p* transitions in potassium ions ranging from K^{2+} to K^{4+}. The current-voltage characteristics of the microdischarge suggest that the source operates in a hollow cathode mode and consequently the emitting ions may be localized on the potassium electrode surface at the hole into the capillary. This compact capillary XUV source with a photon energy of 30 eV is a useful XUV emission source for surface morphology applications [2].

[1] M. Wasamoto *et al.*, Applied Surface Science **255**, 9861 (2009).
[2] T. Higashiguchi *et al.*, Applied Physics Letters **96**, 131505 (2010).

Presenting Author

P8

Rare-earth Plasmas as Next Generation Extreme Ultraviolet Lithography Sources at 6.5–6.7 nm.

Takamitsu Otsuka[1], Deirdre Kilbane[3], John White[3], Takeshi Higashiguchi[1,2], Noboru Yugami[1,2], Weihua Jiang[4], Akira Endo[5], Padraig Dunne[3], and Gerry O'Sullivan[3]

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Nanosecond laser-produced plasmas have been developed as high efficiency and high power sources of extreme ultraviolet (EUV) emission. The development of sources of EUV emission with a wavelength less than 10 nm is a subject of considerable interest. Wavelengths shorter than 10 nm are especially useful for next generation semiconductor lithography toward the final stage beyond the 13.5-nm EUV source [1].

Our first demonstration of laser-produced Gd and Tb plasmas emitting strongly at 6.5–6.7 nm, coupled with a Mo/B_4C multilayer mirror, shows that the opacity of the Gd and Tb plasmas is large. This conclusion is supported by experiments varying the laser wavelength and involving dual pulse irradiation experiments, with Xe and Sn plasmas at 13.5 nm. To increase the CE and the spectral purity, we suggested that it is important to use shorter pulse duration irradiation, a low initial density target and low electron density plasmas (such as CO_2 laser-produced plasmas and/or discharge-produced plasmas) [2]. In this presentation, we show the spot size dependence, electron temperature dependence, and the laser wavelength dependence on the conversion efficiencies and spectra of the Gd and Tb plasmas, together with supporting the numerical analysis.

[1] D. T. Attwood, "*Soft X-Rays and Extreme Ultraviolet Radiation*" (Cambridge University Press, Cambridge, 2000), Chap. 6.
[2] T. Otsuka *et al*., Applied Physics Letters **97**, 111503 (2010).

Presenting Author

P9

Spectral and Temporal Behaviors of Alkali Metal Vapor Extreme Ultraviolet Sources for Surface Morphology Applications

Takeshi Higashiguchi[1,2], Mami Yamaguchi[1], Takamitsu Otsuka[1], Noboru Yugami[1,2],
Rebekah D'Arcy[3], Padraig Dunne[3], and Gerry O'Sullivan[3]

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Photon energies between 10 and 100 eV correspond to wavelengths between 12 and 120 nm in the electromagnetic spectrum. These photon energies are high enough to induce photochemical reactions in most materials, including hydrogen, carbon, and oxygen. Short wavelengths are generally necessary for surface material processing. Light sources in the vacuum ultraviolet (VUV) and extreme ultraviolet (XUV) spectral regions will thus be applied in various scientific and engineering fields, such as semiconductor lithography, diagnosis in dense plasmas, materials processing, photochemistry and biological imaging. A photo-induced desorption spectrometer employing a compact, efficient discharge-produced microplasma XUV source in 20−200 nm broadband spectral region has been proposed, which has the advantage of neither damaging or melting the surface after irradiation [1]. We have characterized the emission spectra of the pure potassium plasma to understand the spectral behavior and the plasma parameter in a compact, discharge-pumped microplasma extreme ultraviolet source [2]. Potassium ions produced strong broadband emission around 40 nm due to *3d*–*3p* transitions in potassium ions ranging from K^{2+} to K^{4+} at the time-averaged electron temperature of about 12 eV. The temporal behavior of the 39-nm emission closely follows the recombination of the 12-eV electron temperature plasma. An atomic process hydrodynamic simulation in the potassium plasma reproduced this temporal behavior.

[1] M. Wasamoto *et al*., Applied Surface Science **255**, 9861 (2009).
[2] T. Higashiguchi *et al*., Applied Physics Letters **96**, 131505 (2010).

Presenting Author

P10

Investigation of Atomic Processes in Laser Produced Plasmas for the Short Wavelength Light Sources

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We investigate the atomic processes of multiple charged ions of elements with Z=50 to 70 for their application to short wavelength light sources. Firstly, we investigate the atomic energy level structure using the calculated atomic data from the HULLAC code.

Secondly, the coefficients of radiative transfer, spectral emissivity and opacity are calculated using the collisional radiative model over a range of electron temperature and ion density. Finally, the conversion efficiency is evaluated on the basis of a simple plasma model assuming isothermal expansion of the laser produced plasmas. It is shown that 4d open shell ions of atomic elements with Z=50-70 have a similar atomic structure, with which strong emission through 4d-4f + 4p-4d transition array is obtained. The wavelength is almost constant over Pd- to Kr-like ions, which decreases as the atomic number increases. Calculation suggests a conversion efficiency comparable to Sn source can be obtained with Gd and Tb sources at the wavelength of 6.5nm. Plasma temperature required for the production of 4d open shell ions is discussed from the calculated ionization balance, and the requirement for the pumping laser power is also discussed.

Presenting Author

P11

Optimization Studies of the LPP Short-wave Radiation Source with Xe Gas Jet Target in the Ioffe Institute

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For several recent years, a laboratory-type photolithography system with desired resolution scale in tens of nanometers and using the EUV radiation range is developed in the Ioffe Institute. One of its main modules is the EUV radiation source. Not being restricted with high productivity demand, the LPP short-wave radiation source with Xe gas jet target has been chosen due to its technical simplicity. Results of preliminary studies of the source under consideration are reviewed in the present contribution.

One of the studies was a computational optimization of the gas-jet target. Based on numerical simulations of the Xe gas jet over a wide range of the nozzle configurations and inlet gas conditions a composite optimization criterion was calculated. Taking into account experiment geometries, dependence of plasma luminosity on the target density, and absorption in the surrounding gas, the criterion made it possible to select optimum configurations for a further experimentation.

Another preliminary research was an experimental campaign with the laser produced plasma in stationary gases at low pressures. The laser spark was ignited with the Nd:YAG laser in several gases, including xenon, at pressures within a range of P = 1 Torr to 1 atm, so that atomic concentrations corresponded to those expected in the jet. Complicated, extended up to several millimeters along the laser beam and symmetric relative to the focus structures of the plasma body were observed. Plasma temperatures around $T_e \approx 30$ eV have been deduced from the measured absorption of the laser radiation in the spark and the spark length.

With the aid of the streak camera, space-temporal plasma evolution has been explored. A mechanism to explain seeming plasma extension rates around 10^7 cm/s has been proposed, and the calculated data were in a satisfactory agreement with the measured ones.

Presenting Author

P12

Computational Optimization of the Gas-jet Target in the LPP Short-wave Radiation Source

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Numerical simulation of Xe gas outflow from a nozzle into the vacuum has been carried out. The simulation was performed for 7 different nozzle configurations and for inlet gas pressures within P_0 = 1 to 10 atm range. Then a composite optimization criterion based on the data obtained was calculated. It included dependences of both the plasma luminosity and absorption in the surrounding gas on the gas density whereby the criterion described the plasma radiation intensity observable on the outside. The latter was obviously dependent on geometry of the experiment – diameter of the plasma body and its position relative to the nozzle edge and the jet axis. Thus, application of the criterion made it possible to select optimum configurations and operational modes for a further experimentation.

Presenting Author

P13

A Study of the Laser Produced Plasma in Stationary Gases at Low Pressures

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The laser spark was ignited with the Nd:YAG laser in air, hydrogen, helium, argon and xenon at pressures within a range of P = 1 Torr to 1 atm. Atomic concentrations corresponding to this pressure range were expected in further experiments where a supersonic gas jet would be used as the target. Plasma photographs demonstrated a complicated, extended along the laser beam and symmetric relative to the focus structure of the luminous body. Its length rised as the pressure increased, reaching up to several millimeters. Plasma temperatures as deduced from the measured absorption of the laser radiation in the spark and the spark length have turned out to be around $T_e \approx 30$ eV.

With the aid of the streak camera, a research of the space-temporal plasma evolution has been realized. A mechanism to explain seeming plasma extension rates close to and more than 10^7 cm/s has been proposed, and the calculated data were in satisfactory agreement with the measured ones.

Presenting Author

P14

Next Generation of EUV Lithography: Challenges and Opportunities

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Reduction of light wavelength and increasing numerical aperture (NA) used in Litho tools has enabled the shrink of printed features to 32 nm half-pitch (hp). Current immersion systems based on 193 nm are printing features as small as 32 nm. State of the art EUV lithography, at a wavelength of 13.5 nm and NA of 0.25 has already demonstrated excellent capability to print 26 nm features and smaller with single exposure, and is expected to enable printing to16 nm hp and beyond by increasing the NA. Yet shrinking the feature size beyond 11 nm will require advanced optical designs that can pose a significant challenge for imaging and productivity for a 13.5 nm based lithography system.

Shrinking wavelength with maintaining or increasing throughput is a traditional way to enable improved imaging for the last 20 years. The transition from 13.5 nm to a shorter wavelength offers the possibility to combine high imaging capabilities with an acceptable process window. Change of working wavelength, though, will introduce changes to a number of subsystems of the lithography system including the source and optics.

Our work is investigating the potential of shorter wavelength litho system performance with particular focus on 6.7 nm. We will review requirements that 6.7 nm systems should meet to enable continuation of lithography roadmap for imaging and productivity. Specifications of the key system elements including source, optics, resist are discussed.

Presenting Author

P15

Principles and Utility of the EUV Laser

Davide Bleiner, Felix Staub, and Juerg Balmer

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Investigations of laser-produced plasmas are of considerable importance to fields such as lithography fusion, x-ray sources, and imaging. By appropriate choice of the laser and lasma parameters, amplification by stimulated emission (ASE) of radiation has been demonstrated in the x-ray spectral region between 4 and 30 nm to date. Refraction losses in the expanding, inhomogeneous plasma have so far limited the x-ray laser efficiencies to 10-6. Solutions to this problem include the use ofmultiple and curved targets and the multi-pulse technique in which a shallow “long” pulse irradiates the target a few nanoseconds before the main driver pulse. In our work on the optimization of soft-x-ray lasers, gain saturation with a gain-length product g·L > 16 has been demonstrated on the 4d _ 4p, J = 0 - 1 laser line in laser-produced plasmas of nickel-like tin at 12nm. In-band energy of 10 μJ is emitted having a divergence of 3 mrad (vertical) and 1.5 mrad (horizontal).

Considering measured pulse duration of 5ps, this implies a peak EUV power in the MW range. The presentation will begin discussing the principles of X-ray laser, and move on showing what the ongoing applications are. In a companion presentation we will present results from one workhorse application, namely imaging at nano-scale.

Presenting Author

P16

EUV Laser Application for Optical Lithography

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The X-ray & laser plasma group at the University of Bern runs a soft Xray laser (XRL) system and is currently developing a 5Hz system, based on non-linear optics oscillator amplification. The former system is based on laser gain amplification of a Nd:glass oscillator pulse over six stages that downstream delivers a 1—20J IR driver pulse of 1.2ps on the target. The line focus is obtained from the focusing mirror astigmatic projection. The plasma ASE-gain column is approx. 60um by 1.2mm, and generates
a 5ps soft X-ray beam with approx. 10uJ. The brilliance of 1027 ph s-1 mm-2 sr-1 0.1%BW is close to that of a free electron laser (FEL). Nevertheless the footprint of <5m2 is much compacter than a FEL, which is appealing for industrial purposes.

Ongoing research activities are thus focused on interfacing the Berne XRL facility to applied projects, most notably EUV lithography (mask metrology) and material science (XPS). Beam extraction and preparation with a dedicated multilayer optics setup is a preliminary task. A nanoimaging microscope is operative and improvements are planned using Fresnel zone plates to achieve actinic resolution and a x-ray back-illuminated CDD. The illustration shows imaging of a reticle using 12nm with a optics-limited resolution of 1um.

Presenting Author

P17

Development of Reflective Coatings for BEUV Lithography

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The status of research and development of multilayer coatings for near 6.7 nm application, fabricated using magnetron sputtering techniques, will be described. This is an initial phase of the project aimed at approaching near normal incidence peak reflectivity values of 63-67% and 66-70%, calculated for La/B_4C and La/B_9C structures with an inter-layer zone width of 0.4-0.3 nm.

For non-polarized radiation at 6.69 nm, reflection coefficients in the range 40–60% have been obtained. Structures with large periods ($d \approx 7$ nm) exhibit reflectivity close to theoretical limits. Reflection coefficients of 45% at normal incidence, measured on multilayer mirrors (MLM) with small periods ($d \approx 3.4$ nm) are still essentially below the predicted level for these structure compositions. We found, that this discrepancy is mainly caused by relatively broad interlayer zones, resulting from interaction of B with La, featured with high chemical activity.

Indirect analysis indicates large broadening of the La-on-B_4C interface. We proposed and tested a reliable method to reconstruct the depth profile of permittivity from grazing incidence X-Ray (0.154 nm) diffraction patterns. This method can be used to rapidly estimate the degree of interface asymmetry and the width of transition interlayer boundaries.

Deposition of barrier anti-diffusion Cr, Mo, or Sn inter-layers 0.3–0.5 nm thick did not improve the reflection characteristics of the MLMs. We have concluded, that a further increase of the barrier thickness cannot be effective, since the La layer thickness in the normal incidence La/B_4C structure, optimized for maximum reflectivity, is just about 1.5 nm. One of the possible solutions to this problem is to replace the La layer in La/B_4C by its stable chemical compound with satisfactory optical characteristics in the vicinity of 6.7 nm. Preliminarily calculations demonstrate that this approach is realistic.

Perspectives of further upgrade and planned steps will be considered, associated with the current work on instrumentation upgrade, aimed at providing super-fine treatment of interfaces.

Presenting Author

P18

Modelling of Laser Produced Gadolinium Plasma Source at 6.7 nm

V.Novikov[1], V.Ivanov[2], K.Koshelev[2], V.Krivtsun[2], A.Grushin[1], A.Solomyannaya[1],
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An efficiency of LPP gadolinium plasma in BEUV spectral region is investigated by using the code RZLINE.

The 2D RHD Eulerian code RZLINE makes possible self-consistent calculation of level kinetics and radiation transport for different plasma configurations arising from extreme heating by laser pulse. It includes processes of evaporation and condensation, reflection of laser beam, opacity effects and so on. We have calculated the detailed spectra of laser produced Gd plasmas with Nd and CO2 laser beams at different pulse energies, pulse durations and power densities (different focal spots) for plate and droplet Gd targets. The CE coefficient, anisotropy of radiation, size of source and other characteristics of the source were obtained in a wide region of input parameters for 0.5% bandwidth for different wavelengths in 6.5 – 6.9 nm region. The calculated data are compared with experiment.

Presenting Author

P19

New Type of DPP Source for EUVL Based on Liquid Tin Jet Electrodes

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A new approach for DPP EUV sources based on usage of two liquid metallic alloy jets as discharge electrodes has been proposed and tested. Discharge was ignited using laser ablation of one of jets (cathode). A system with two jet electrodes was tested at repetition rate up 1 - 5 kHz with dissipated electrical power up to 20 kW. Radiating spectra, time characteristics, CE are similar to conventional DPP schemes with rotating wheels. In first experiments Ga:Sn eutectic alloy which is liquid at room temperature was circulating in a closed loop.

High velocity of the jets (30 m/sec) ensures a renewed electrode surface for every next shot for repetition rate frequency up to 30-50 kHz and provides effective heat transportation from discharge zone. Modeling and experiments demonstrates that the proposed scheme is able to dissipate up to 200 kW of electrical power without overheating of nozzles and tin surface.

It was found that flexible electrodes configuration allows channeling of essential part of debris plasma in directions opposite to EUV collector.

Presenting Author

P20

Modelling of Laser Produced Gadolinium Plasma Source at 6.7 nm

V.Novikov[1], V.Ivanov[2], K.Koshelev[2], V.Krivtsun[2], A.Grushin[1], A.Solomyannaya[1],
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Presenting Author

P21

EUV/Soft X-ray Development at Energetiq Technology

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The EQ-10 is a commercially available, medium-power (10 W /2 pi,13.5nm +/- 1%, Xenon) EUV source suitable for a variety of resist exposure, mirror testing, and inspection applications. The EQ-10 platform can also be used to generate soft x-ray photons by using Nitrogen as a source gas (400mW/2 pi, 2.88nm ,Nitrogen). Since the launch of the product in 2005, significant field experience and product customization has taken place. Recent redesign for optimization of pulse to pulse stability has been implemented. Data will be shared on this improvement.

Energetiq will share some current applications of the more than 15 sources in the field. We will also share some biological images taken with the Soft X-ray source.

Presenting Author

P22

EQ-10 Electrodeless Z-Pinch EUV Source for Metrology Applications

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Now that EUV lithography systems are beginning to ship into the fabs for next generation chips it is more critical that the EUV infrastructure developments are keeping pace. Energetiq Technology has been shipping the EQ-10 Electrodeless Z-pinch^{TM} light source since 1995. The source is currently being used for metrology, mask inspection, and resist development. These applications require especially stable performance in both output power and plasma size and position.

Over the last 5 years Energetiq has made many source modifications which have included better thermal management as well as high pulse rate operation. Recently we have further increased the system power handling and electrical pulse reproducibility. The impact of these modifications on source performance will be reported.

Presenting Author

P23

5 sr Collector Mirror Coatings for High Power Laser Produced Plasma EUV Sources

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Bringing EUV Lithography forward to high volume manufacturing, one of the main challenges to date is to deliver a high level of EUV power at intermediate focus. One of the most promising methods to meet the joint requirements from all leading scanner manufacturers is a high power laser produced plasma source. The required 13.5 nm radiation is generated by highly ionized plasma which is created by depositing laser energy at 10.6 µm wavelength into tin. The radiation of this plasma is collected by a 5 sr near normal incidence EUV collector (Ø 660 mm) and focused to the IF.

The paper presents the successful coating of the world’s largest ellipsoidal EUV collector mirror with a diameter of 660 mm. A maximum reflectivity of the laterally graded Mo/Si multilayer of more than 65 % was achieved for radii smaller than 230 mm. For radii between 240 and 325 mm the reflectivity decreases to a minimum of 59 %. The wavelength remains constant at (13.50 ± 0.50) nm over the entire collector surface which is well within the specifications for HVM.

Presenting Author

P24

Metal Impurities in LiF: Opportunity for X-ray Imaging Detector Development

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Nowadays there is a great interest in the technological research about luminescent materials. Novel miniaturised devices based on lithium fluoride (LiF) containing active colour centres are under study for applications in photonics [1]. Moreover, LiF crystals and thin films were also proposed as novel extreme-ultraviolet (EUV) and X-ray imaging detectors based on the photoluminescence (PL) of colour centres [2]. Several peculiar features of LiF-based detectors, like very high spatial resolution over a large field of view and wide dynamic range make them very promising as imaging plates for EUV and X-rays. An attractive opportunity in order to improve their performances is expected from metal-related defects embedded in crystalline host matrix. Recently, it was shown that the presence of some impurities (Pb and Tl) into the raw LiF salts and crystals drastically modifies the PL properties of stable F_2 and F_3^+ colour centres [3]. The aim of this paper is to study the influence of the metallic ion doping in the LiF matrix and their stability during annealing procedure by optical spectroscopy techniques and X-ray Absorption Spectroscopy (XAS) measurements. Future developments are foreseen in the production of pure and doped LiF thin films as novel radiation detectors of increased sensitivity.

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[3] F. Somma, R.M. Montereali, M.A. Vincenti, S. Polosan, M. Secu, *Growth and characterization of Pb-, Tl-doped LiF crystals*, Optical Materials 32 (2010) 1309–1312.

Presenting Author

P25

Multilayer Optics for EUV and Beyond

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In order to structure and to observe the world in more detail much progress was made in the enhancement of optical resolution the recent years. This fact goes along with an increasing demand in optical components for wavelengths smaller than 100 nm for a wide field of applications in the EUV and X-Ray range. At Fraunhofer IOF, Jena, the optical development covers this range down to 1.0 nm.

Due to the absorption of these wavelengths within a few nanometers, interfering multilayer reflection optics must be used to collect and guide the light. Possible applications will be presented in this paper and mainly include several types of optics for the EUV lithography at 13.5 nm, but also mirrors for space research, material characterization, X-ray microscopy, etc. with regard to the present knowledge in design, characterization, stability and enhancement of optical properties.

Presenting Author

P26

Scattering of CO_2 Laser Radiation on Tin Plasma Targets

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Effective coupling of laser radiation to plasma is essential for achieving high conversion efficiency of LPP based EUV sources. Among other, poor coupling may result in high reflectance of plasma, which causes laser radiation propagation into the litho system resulting in heating of the optical elements and wafer. In our work we study CO2 laser interaction with plasma in LPP sources of EUV radiation. Theoretical modeling is based on the simulation in a complex 2D geometry for non-homogeneous non-stationary plasma. All essential processes are included in calculations: target evaporation, plasma hydrodynamics, level kinetics and radiation transport using several thousands photon frequencies to represent in detail each spectral line. Dynamics of absorption, conversion efficiency and angular distribution of scattered laser radiation is calculated and compared for different types of tin targets among which are spherical droplet and pre-pulse split droplet. It is shown that in case of single droplet the significant part of incident radiation is reflected back with respect to the direction of the laser beam. Split targets are found to be more efficient absorbers, which is caused by more intensive plasma spread and consequent smooth gradients of electron density.

Presenting Author

P27

Are the Extremely Hot Oxygen and Nitrogen Plasmas the Debris-less Soft X-ray Light Source?

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The 1s-2p transition of O VIII has the wavelength of 1.9 nm. Recently we have observed the soft X-ray emission spectra in collisions of O^{8+} (bare ion) with He and H_2 gases with a window-less type Si(Li) detector. In this charge exchange collisions, the intensity of the 1s-2p transition of O VIII is extremely strong. Now we consider the recombination phase of the extremely hot oxygen plasma as a new candidate of debris-less soft X-ray light source. Because the mechanism of the emission in N^{7+} (bare ion) collisions should be same as the oxygen ion case, the 1s-2p transition of N VII with the wavelength of 2.48 nm can be another candidate of a debris-less emission light source. As atomic physicists, we just show the experimental results on the elementary atomic processes. We hope that the engineering researchers consider and demonstrate the feasibility of this type of soft X-ray light source for the beyond 13.5 nm EUV lithography.

Presenting Author

P28

Results Obtained with High Efficiency Gratings for EUV Application, EUV Interferometer Application, EUV Source Specifications

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EUV lithography could be planned to address the 22 nm node and beyond. Limit of resolution of the chemically amplified resists is one of major issue for EUV lithography development. Currently, studies and researches concerning limit of resolution of the resists are done in interferometer tools using synchrotron radiation or EUV steppers.

In framework of the stand alone EUV interferometer development, due to the low power of EUV sources, LETI has studied new gratings, EUV source methodologies characterization and interferometer design. In this work, we developed new gratings for EUV applications with a theoretical efficiency of 25% compared to gratings currently used in EUV interferometer (7% efficiency).Manufacturing process to realize 100 nm thick silicon membranes and gratings etched in molybdenum layer were developed. This high efficiency is a necessary step to imagine a successful standalone EUV interferometer development. Membrane and gratings characteristics will be described (size and materials). Exposure tests have been achieving using synchrotron radiation. Results obtain with first and second order diffraction will be presented.

Source methodology characterization will be discussed as well as specifications of the EUV source needed. Finally, the design of the EUV interferometer selected will be presented.

Presenting Author

P29

Development of multilayer spectral purity filters for EUVL Tools

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In previous presentations we reported on free-standing Zr/Si multilayer film structures as spectral purity filters (SPF) for application under Alpha Demo Tool conditions and in EUV metrology.

The work in the last two years was aimed at drastic upgrade of major SPF parameters to match requirements of HVM tools, first of all sustainability to much higher power loads in prolonged exposures. Taking into account expected characteristics of potential HVM EUV sources, stopping IR radiation at 10.6 nm, adaptation to power load modulation in various operation modes, exploitation in hydrogen environment constitute new essential development tasks.

We shall present recent results, obtained with structures containing layers of molybdenum and silicides of molybdenum and zirconium. The new SPFs are featured with inband transmission above 72-74%, suppression of the 10.6 nm radiation down to <1%, a very low (<0.1%) transparency for DUV radiation. Samples were tested using a CO_2 laser beam at absorbed power loads up to 8 W/cm^2 in 2-3 hour exposures at related temperatures above 1000 °C. Exposures at absorbed power loads up to 5 W/cm^2 (950 °C) lasted 18-20 hours with power modulation, simulating machine conditions. Post exposure examination showed negligible variations of DUV and IR transmission, but a small (1-2%) decrease of inband transmission. The latter is assumed to result from a high temperature oxidation of the structure, which remains a subject of further SPF development work.

Also presented will be large samples with a clear aperture of 160 mm, demonstrating the possibility to fabricate SPFs with HVM compatible dimensions.

Presenting Author

P30

Design of a clean, high brightness light source for EUV lithography research in shorter wavelength region

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Recent progresses of high average power pulsed CO2 lasers and high intense electron beam make it possible to produce milli-watt class EUV light source via laser-Compton scattering. Laser-Compton X-ray beam has a good directivity and angularly distributed quasi-monochromatic spectrum, and the wavelength of the X-ray is short enough even though the electron beam energy is several MeVs, because the undulation period of electron, i.e. the laser wavelength, is much shorter than that of magnetic undulators.
These properties meet requirements in the course of 6.7nm lithography research.

We propose two types of designs, low repetition case and high rep. case, and the latter is based on pulsed CO_2 laser beam stored in optical super-cavity.
Low rep. case (100kHz) consists of matured technologies and able to produce 10micro-watt 6.7nm light. High rep. case (100MHz) needs R&Ds for both electron beam and CO2 laser, however, is to be realized in near future. This case shall achieve more than 1 mW.

The designs of our 6.7nm EUV source, the objectives of R&D and future vision of our design is to be presented in the conference.

Presenting Author

P31

Status of EUVL Multilayer Optics Deposition at RIT

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Multilayer optics is a key component of any EUVL system. Variety of material combinations and d-spacing designs are in use depending on application. Sizes are from few millimeters to hundreds millimeters. Different deposition technologies are used. Magnetron sputtering and electron beam evaporation are typically applied for collector, illumination and imaging optics, and ion beam sputtering is a common technology for mask blanks deposition.

RIT, former Osmic, has been involved in deposition of Mo/Si multilayers since late 80’s when timid steps on EUVL just started. RIT coated first imaging optics in 90’s,more than a thousand mask blanks for EUV LLC in 1999-2000, many optics were delivered from RIT between 2000 and 2005. Maximum size of optics being deposited at RIT in the past was 360mm. Growing demand for a bigger size condensor optics convinced us to upgrade one of our deposition system. Capability of this system will be discussed in the paper.

We restarted our activity on developing multilayers for next generation EUVL, for shorter than 13.5nm wavelengths. First normal incidence La/B4C structure for 6.7 nm was deposited at RIT in 2000. Maximum reflectivity measured at CXRO at that time was 43%. We will present new results with this structure. Also, multilayers for wavelength range of ~7nm to 11nm are in development as well. Some preliminary results will be discussed.

Presenting Author

P32

Influence of High Energy Electrons on EUV and Soft X-ray Emission Spectra of Non-equilibrium Plasma

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The soft X-ray radiation in water window region can be produced from 2p-1s and 3p-1s resonant transitions in N VI and N VII ions. In EUV range, an emission at 2% band 13.5 nm may be obtained from 5p-4d resonant transitions in Xe XI and from the set of satellites and resonant transitions in highly charged Xe XVII - Xe XXXV ions as well. Such highly charged ions have a high ionization potential in comparison with plasma temperature in most of laboratory plasmas. Fast electrons generated in different types of nonequilibrium plasma like discharge, solar, laser etc at relatively small portions may have a significant influence on level populations and produce highly charged ions, thus the line emission intensities, despite on low plasma temperature. In the report the influence of fast electrons on the line emission from xenon and nitrogen ions is considered and the maximum emission conditions are explored. Fast electrons distribution functions are added into impact processes kinetics based on the distorted waves approximation with Hartree-Fock-Slater quantum-statistical model. In particular, conditions for highly charged Xe ions generation and increase of the emission in the 13.5 nm EUV range are found. The emission at water window band from nitrogen plasma may be increased substantially in a narrow range of parameters also. Efficiency of discharge- and laser- produced plasma soft X-ray and EUV sources in required narrow bands is discussed.

Presenting Author

P33

High intensity EUV and soft X-ray plasma sources modelling

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The average power of EUV sources at IF required for lithography HVM is higher than presently available. At the same time, for actinic mask blanks, patterned mask and in-situ inspection tools, EUV sources of moderate power but very high brightness are required. In practice, the non-equilibrium plasma dynamics and self-absorption of radiation limits the in-band EUV radiance of the source plasma, and the etendue constraint limits the usable power of a conventional single unit EUV source. Under those conditions one of the primary goals in the development of EUVL is the modelling of plasma-based light sources created by intense lasers and high-current pulsed discharges. A new generation of the computational code Z* is currently developed under international collaboration in the frames of FP7 IAPP project FIRE for modelling of multi-physics phenomena in radiation plasma sources to contribute considerably to solving current EUVL source problems as well as extending their application to subsequent nodes (16nm and beyond) and to shorter wavelength radiation applications. The radiation plasma dynamics, the spectral effects of self-absorption in LPP and DPP and resulting conversion efficiencies are discussed. The modelling results are guiding a new generation of multiplexed sources being developed at NANO-UV, based on spatial/temporal multiplexing of individual high brightness units, to deliver the requisite brightness and power for lithography, actinic metrology and soft X-ray imaging applications.

Presenting Author

P34

Multiplexed EUV Sources based on a Compact Module with High Irradiance and Low Etendue for Actinic Inspections and Metrology Applications

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The roll out of EUV lithography for HVM demands reliable and powerful radiation sources in the EUV spectral range. NANO-UV is delivering a new generation of compact EUV light sources. This paper presents an update on CYCLOPS™, an EUV light source developed for EUV lithography applications. The emitting plasma is generated by a fast micro plasma pulsed discharge incorporating the i-SoCoMo™ technology, where a micro plasma pulsed discharge source is integrated to a photon collector based on an in situ active plasma structure. The source module can be optimized to operate at high power or high irradiance. Without the use of external physical optics, the peak irradiance of the current GEN-II source is measured at 62 cm away from the source to exceed 1E18 ph/cm2/s, in a 3 nm bandwidth around 13.5nm, with the source operating at up to 0.5 J per pulse at 3 kHz in xenon containing admixture with a typical etendue below 1E-2 mm2.sr. Using a number of such source modules, we are developing light sources with the requisite brightness and power to address the mask metrology needs, with spatial and temporal multiplexing – the HYDRA™ design. A complete optical characterization of the EUV radiation in terms of brightness, power, and etendue will be reported as well as measured data from the 4 units multiplexed source for blank inspection.

Presenting Author

P35

Time and Space Resolved Optical Plasma Diagnostics of Table-Top Scale Laser Produced Tin Plasmas

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We are currently at the early stages of an optical diagnostic study of laser plasmas formed on solid Sn targets in selected configurations. Our specific aim is to generate density-temperature maps for various laser power densities, wavelengths and target geometries to compare with values from predictions for optimised EUV emitting parameter sets. Plasmas are generated by a Surelite™ III-10 Nd-YAG laser which can be operated at the fundamental (1064 nm) or its harmonics (532 nm, 335 nm or 266 nm). Spectra are recorded on a stigmatic spectrometer (0.5m Chromex™ UV-Vis / Czerny-Turner mount) equipped with an Andor™ ICCD camera operated in 2D (imaging mode) with a minimum gate width of 3 ns [1 – 3].

Spectra, extending from near UV to the near IR, and plasma parameters extracted from selected lines, will be presented. The focus of the poster will be on diagnostic line selection and its power density dependence.

It is planned that the system will, in time, permit the correlation of EUV emission with source plasma parameters in real-time, a future goal of the project.

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Presenting Author

P36

Time Resolved EUV Emission Spectra of Table-Top Scale Laser Produced Tin Plasmas

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To date lithography has been at the forefront of feature size reduction due to the ready availability of intense light sources with ever decreasing wavelength. However, to make further progress new lithography techniques are needed, with extreme ultraviolet lithography, or EUVL, the most promising candidate [1].

One current candidate for the EUVL light source is a tin plasma. Modelling predicts that laser produced tin plasmas, with electron temperatures of 30 to 70 eV can emit brightly in the desired bandwidth [2]. Emission in the vicinity of 13.5 nm can be ascribed to overlapping transitions involving the 4d-subshell in Sn^{7+} to Sn^{12+} ions, which merge to form an unresolved transition array (UTA) [3]. We will present time resolved spectra of tin plasma UTA in the 9–18 nm region.

The plasmas were produced by focussing a 500 mJ, 16 ns FWHM, laser pulse from a Q-switched Nd:YAG laser to a power density of $< 10^{11}$ Wcm^{-2} onto a pure tin bulk target. The resulting time (~8 ns) and spectrally (Dl ~ 0.01 nm) resolved EUV spectra are compared with atomic structure calculations, performed with the Cowan suite of codes [4], to determine the dominant ion stage as function of time.

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Presenting Author

P37

Advanced INNOSLAB solid-state-lasers for XUV/EUV-generation

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Apart from the high-throughput lithography of semiconductor chips many additional applications of EUV/XUV-radiation are developing such as mask inspection, water-window microscopy, reflectometry for the structural and chemical analysis of thin layers. For these applications as well as for lithography two different light-source technologies are competing: the discharge produced (DPP) and the laser produced (LPP) sources, where especially the LPP has advantages in those metrology applications, requiring high brightness. For efficient conversion of the laser power into XUV/EUV-radiation several conditions have to be met, such as pulse length around ns, high beam quality in order to achieve the required laser intensity and average laser power to meet the requirements for the average XUV/EUV-power of the metrology application.

Such lasers are not commercially available and here some development is needed, especially with respect to average power and cost-of-ownership. Fraunhofer-ILT is focusing on solid-state-laser based concepts for the LPP-source and has developed a laser for a high brightness LPP-source in the XUV-wavelength range around 2,5 nm. The laser is based on a chain of slab-type amplifiers according to the INNOSLAB-concept and currently is producing approximately 300 W average output power, with pulse energies of about 150 mJ, rep. rates of about 2 kHz and near fundamental mode quality.

Presenting Author

P38

High-order Harmonic Radiation from Laser Plasmas

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High-order harmonic generation (HHG) is a promising technique for obtaining new sources of coherent radiation since it provides a probe for investigating the interaction mechanism of the solid system with an intense laser field and has the potential to become the future coherent XUV source [1]. We discuss here a novel technique for the production of HHG. A nanosecond laser with focused intensities of the order of 10^{11}W/cm^{2} is employed to produce stagnation layer from colliding plasmas. A short (30 fs) terawatt pulse with focused intensities of the order 10^{15} - 10^{18}W/cm^{2} interacts with the stagnation layer producing HHG. The stagnation layer provides a medium which changes much more slowly than the driving colliding laser plasmas, resulting in a predictable and relatively slowly varying ion/electron density and temperature which evolves over hundreds of nanoseconds [2]. Moreover, the length of the stagnation layer can be varied from a few hundreds of microns to tens of millimetres and can be produced with any solid. Phase matching is possible in such a method and its consequence is a considerable increase in the efficiency of conversion of radiation to a harmonic with a given number.

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Presenting Author

P39

Understanding the Behavior of Laser-produced Tin Plasmas by Time-resolved Spectroscopy and Simulation of their Spectra

Imam Kambali, Tom McCormack, Enda Scally, John White, Gerry O'Sullivan, Fergal O'Reilly and Paul Sheridan

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The temporal evolution of the tin unresolved-transition array (UTA) responsible for the peak extreme ultraviolet (EUV) emission is studied by recording the EUV spectra from laser-produced tin plasma as a function of time using an ISAN 0.25-m grazing incidence spectrograph which covers the wavelength ranges of 10 – 30 nm. This paper reports the experimental results for a 10 ns gate width with 2 ns time steps which confirm that the development and collapse of the UTA follow the temporal behaviour of the laser pulse. As well, a wide range of electron temperatures from 20 eV to 50 eV were simulated using the collisional-radiative (CR), steady state model of Colombant and Tonon, which calculated the fractional ion densities in the plasma to fit the experimental results for each time delay in the early stages of the EUV emission. It is found that the electron temperatures in the early stages of the EUV emission (t = -6 ns to t = -1 ns relative to the EUV peak) are theoretically estimated to be between 35 – 40 eV. The spectra broaden toward longer wavelengths as the plasma cools down which indicates that lower ion stages contribute. This trend gives rise to the self-absorption features near the end of the plasma which, based on the theoretical calculations, are due to SnVI – SnXI.

Presenting Author

P40

Laser-produced Plasmas of Gold-tin Alloy for EUV Sources

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Extreme Ultraviolet (EUV) spectra from laser-produced plasmas of a gold-tin alloy have been recorded for a number of power densities by varying the incident laser energy and lens focusing conditions. 1064-nm pulses from a Nd:YAG laser were focused onto a 100-µm thick foil target of 80%Au-20%Sn alloy while the spectra were captured by a 0.25-m Jenoptic spectrograph which covers the wavelength range of 9.2 – 18 nm. The experimental results show that the bright EUV emissions appear at all wavelength ranges, though emission between 13 – 18 nm wavelengths is brighter than those at shorter wavelengths and the intensity is nearly flat. There is no significant difference in the EUV spectra at high power densities of up to 3.1×10^{12} W/cm^2, however self absorption features are more pronounced at lower power densities due to lower ion stages of tin ranging from Sn IX – SnVII. To better understand the spectral behaviour of each element in the alloy, pure tin and gold targets were fired under the same experimental conditions as the AuSn alloy. At high power densities of ~10^{12} W/cm^2, high ion stages of tin and gold of up to Sn XXII and Au XXV are observed in the spectra respectively. It is also clear that the alloy of gold and tin significantly helps reduce self absorption features at longer wavelengths compared to the pure tin plasmas.

Presenting Author

P41

Robust Liquid Metal Collector Mirror for EUV and Soft X-ray Plasma Sources

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Focusing 13.5 nm light requires mirrors that are essentially atomically flat. Maintaining this high level of finish in front of a hot, debris producing, tin plasma is proving extremely difficult for extreme-ultraviolet (EUV) source manufacturers.
Our solution is to apply a thin coating of a liquid metal to the inside of a solid collector mirror shell, as the surface of clean liquid metals is atomically flat. This liquid metal is chosen as a compromise between EUV collection efficiency and low melting point. Initially we have chosen a room temperature liquid metal, an alloy of gallium, indium and tin. Since the liquid metal is a tin alloy, particles or ions impinging on and sticking to the mirror surface will flow into the liquid mix, maintaining the ultrapolished finish required. These mirrors should provide significantly longer lifetimes than the current state of the art solid mirrors, and remove or reduce the need for debris mitigation.

We report on the results of both EUV and optical tests carried out on a focussing liquid metal mirror.

Presenting Author

P42

Interference Lithography of Graphene Oxide with a Table-top X-ray Laser Source

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X-ray Interference Lithography (XIL) performed with the use of a table-top X-ray source represents a tempting low-cost alternative to the standard techniques adopted in the microelectronic industry for the fabrication of miniaturized devices. With this technique it is well established that large area (up to 8 mm^2) periodic structures (lines) can be engraved onto Polymethylmethacrylate (PMMA) on Si without making use of masks in a simple one-mirror interference setup (Lloyd's configuration), exploiting the coherence properties of a table-top capillary discharge plasma source (λ = 46.9 nm, 1.5 ns pulse duration, 0.1 Hz repetition rate, 150μJ per pulse). Beyond this state of the art, in this paper we present very recent results on the selective lithographic reduction of dip-coated monolayers of graphene oxide, producing on a large area alternating ribbons of reduced graphene and graphene oxide.

Presenting Author

P43

Z-pinch Discharge in Laser-Produced Plasma

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Previously, fast, high current electrical discharges in laser produced plasma (LPP) have been used to compress and heat the plasma to make a pulsed X-ray source. The interaction of the high current and the self-induced magnetic field leads to radial compression of the plasma to form a micro Z-pinch. This technique has also been explored for the generation of radiation at 13.5 nm for extreme ultraviolet lithography.

Here we describe the results of an experiment to investigate the behavior of a relatively low current discharge in a LPP. The LPP was produced with a 20 ns Excimer laser. The discharge was fed by a 1.5 μF capacitor charged to 1 kV and is self-triggered when the plasma column reaches the live electrode. The discharge was underdamped with a period of 2 μs and a peak current of 3.5 kA.

Time-resolved imaging shows that Z-pinching of the plasma occurs but that the compression is limited by the onset of the kink instability. The emission spectroscopy shows that the plasma temperature and degree of ionization increase with the charging voltage.

Presenting Author

P44

Tin Target Modeling for 13.5 nm LPP EUV Source

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Maximizing the conversion efficiency (CE) of extreme ultraviolet radiation to laser energy is paramount to producing an optimum next generation lithography light source at 13.5 nm. Laser-produced plasma emission from Sn IX–Sn XIV ions is one proposed solution. The effect of target geometry for a Nd:YAG laser pulse incident on solid tin using a 2-dimensional code is analyzed to determine optimum conditions for maximum brightness. Previous studies have shown a CE of 1.5% on planar and spherical bulk targets. Here, we obtained a 54% increase in calculated CE using a 1-μm thick ribbon as compared to the bulk target.

Presenting Author

P45

Towards Shorter Wavelength EUV and Soft X-ray Sources

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Sn has been selected as the element of choice for use in sources for EUV lithography at 13.5 nm as it the strongest emitter at this wavelength. This intensity arises as resonance transitions from many ion stages overlap in a narrow wavelength range. The emission is well known to arise from $\Delta n = 0$, 4→4 transitions involving ions with an open 4d subshell and the plasma conditions needed to maximize it have been studied in considerable detail [1]. Similar transitions in higher Z elements have also been observed and move to shorter wavelengths with increasing atomic number [2]. We have recently made a systematic theoretical study of the emission from lanthanide ions using the FAC code [3] and compared the results with available experimental results. In particular we have systematically studied the emission of Gd and Tb ions which lie in the reflectance region of Mo/B_4C multilayer mirrors for which a 40% reflectivity has been obtained [4]. At much higher atomic number, the $\Delta n = 0$, 4→4 array of tungsten is known to dominate the EUV losses from fusion devices when used in a plasma facing component [5]. From these results we can infer that the dominant emission arises from Ag-, Pd- and Rh-like ions. However a major theoretical challenge will be to model the emission from ions whose lowest configurations contain open 4f subshells. Here 4f, 5p and 4f, 5s level crossings greatly complicate the level structures in low and intermediate ion stages. Recent results relevant to this topic will also be presented.

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Presenting Author

P46

Interference Lithography at 11 nm with a Laboratory Gas Discharge Source

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In this work the feasibility of using a Talbot self-imaging effect for EUV interference lithography with laboratory gas-discharge sources is studied. Analytical modeling together with ray-tracing simulations are employed to formulate the requirements to emission parameters. Emission of gas discharge source was optimised to achieve highest possible intensity within 3.2% bandwidth. Free standing thin Nb membranes for necessary transmission masks were manufactured with areas exceeding 0.2 mm^2 and patterned with e-beam lithography.

The obtained experimental and analytical results show that achromatic Talbot interference scheme allows reduction of a period of structures from mask to wafer and can be efficiently used for EUV-IL with an incoherent source, especially for structures with critical dimensions in sub-50 nm range.

Presenting Author

P47

GIXUVR- Grazing Incidence Extreme Ultraviolet Reflectometry: An All-Optical Technique for Metrology of Ultra-Thin Layers

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In order to miniaturize today's metal oxide semiconductor field effect transistors even further, channel lengths and gate dielectric thicknesses need to decrease. Due to rising leakage currents traditionally deployed SiO2 dielectrics need to be replaced by alternative (high-k) materials with a larger dielectric permittivity in the future. A current focus of the industry is centered on thin films of HfO2 as a promising candidate for further scaling. Characterization of these layered systems is mandatory to measure and control the interface between substrate and high-k material as it can severely influence its electric properties. Here we propose a novel metrology technique, namely Grazing Incidence Extreme Ultraviolet Reflectometry (GIXUVR), utilizing short wavelength radiation from off-synchrotron sources for the analysis of such thin-film structures. Benefits of the method are the rapid measuring time on the order of milliseconds to seconds, high thickness and material sensitivity due to very efficient interaction of XUV light with matter.

Our poster addresses the challenges and achievements in utilization of XUV radiation from laboratory sources for metrology of ultra-thin layers (< 10 nm) where other all-optical techniques are reaching their limit due to lack of contrast. In a polychromatic approach one is able to determine a surface-sensitive characteristic reflectivity by monitoring the incident and emergent spectrum before and after the sample using two independent detectors. Feasibility of the method was tested by the investigation of oxides on wafers as well as hidden ultra-thin oxide interlayers as a challenge for future metrology of high-k stacks.

Presenting Author

P48

EUV Dark-Field Microscopy for Actinic Defect Inspection

Aleksey Maryasov[1,2], Stefan Herbert[1,2], Larissa Juschkin[1,2], Anke Aretz[2,3], Klaus Bergmann[4], Peter Loosen[1,2,4], Rainer Lebert[5]

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One of the important requirements for EUV lithography is an extremely low amount of critical sized defects. A reliable and fast inspection of mask blanks is still a challenge. Here we present the benchmarking of the actinic Schwarzschild Objective based microscope operating with an EUV-LAMP discharge source from BASC. Artificial test structures (pits and bumps) and natural defects on multilayer mirrors were measured with the EUV microscope and characterized with an atomic force microscope (AFM). Defect size sensitivity of actinic inspection in dark field mode without resolving the defects was investigated. The relation between defect shape and size and its scattering signal is discussed.

The EUV illumination efficiency and clean room conditions of the setup were upgraded enabling an investigation of real mask blanks. The performance of the new setup is presented. Defect detection limits with a large field of view (FOV) and moderate magnification are discussed in terms of required source photon flux and detection camera performance. Extrapolation of the results envisions a compact laboratory tool realization with sub-30 nm sensitivity and significant throughput.

Presenting Author

P49

X-ray Optics for the LCLS Free-electron Laser

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This presentation discusses the development of novel, diffraction-limited reflective optics (mirrors and gratings) for the Linac Coherent Light Source (LCLS), the first x-ray free electron laser (FEL) in the world. This first-of-a-kind source produces ultra-short (~100 femtosecond) monochromatic x-ray pulses of unprecedented brightness [10^{32} photons sec^{-1} mm^{-2} mrad^{-2} (0.1% bandwidth)-1] in the first harmonic, ranging between 0.8 and 8 keV. The revolutionary capabilities of the LCLS will generate a wealth of new research in the fields of physics, biology and materials science. The extremely high instantaneous dose of the LCLS beam places strict limits on the materials choice, thus leading to an x-ray mirror design consisting of an especially modified reflective coating (boron carbide or silicon carbide) deposited on a silicon substrate. Furthermore, the requirement for preservation of the coherent wavefront of the LCLS beam results in stringent surface figure and finish specifications that challenge the state-of-the-art in substrate manufacturing, thin film deposition, metrology and mounting capabilities [1-4]. Experimental results on the development, optimization, and characterization of the LCLS x-ray mirrors and gratings are presented and compared with theoretical models. The stress, microstructure, and damage threshold properties of the reflective coatings developed for the LCLS will also be discussed [5-8].

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Work was supported in part by DOE Contract DE-AC02-76SF00515. This work was performed in support of the LCLS project at SLAC.

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Presenting Author

P50

Liquid-jet Water-window Sources for Nano-scale Imaging

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We develop compact high-brightness liquid-jet x-ray sources that enable laboratory x-ray imaging at the nanoscale.

Our work-horse are laser plasmas employing liquid-jet-targets for high-rep rate regenerative operation. Here the λ=2.48 nm emission from a liquid-nitrogen-jet laser-plasma [1] is combined with state-of-the-art normal-incidence multilayer condenser optics and 20-nm zone-plate imaging optics to demonstrate laboratory water-window x-ray microscopy[2] with < 25 nm resolution and synchrotron-like image quality on biological and soil science samples. The source is presently upgraded with a 0.8 ns/2kHz/280 W Nd:YAG slab laser with the goal to reach bending-magnet water-window brightness. Other developments include tomography for 3-dimensional imaging [3], 13-nm zone width diffractive optics [4], compound zone plates for higher-efficiency imaging [5], and, recently, 3D tomography for imaging of cryo-fixed biological samples [6]. In addition we have recently started an effort to develop a high-brightness source based on a focused electron-beam impacting a liquid water jet resulting in 2.36 nm emission [7]. The principles and scalability of this source will be discussed.

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[3] M. Bertilson, O. v Hofsten, U. Vogt, A. Holmberg, H. M. Hertz, Opt. Express. 17, 11057 (2009)
[4] J. Reinspach, M. Lindblom, O. von Hofsten, M. Bertilson, H. M. Hertz, and A. Holmberg, J. Vac. Sci. Technol. B 27, 2593 (2009).
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Presenting Author

P51

Optimization of CO_2 Laser-produced Sn Plasmas for Next Generation Semiconductor Lithography Sources

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Research to date [1] has identified CO_2 laser produced plasmas (LPPs) of Sn as a viable EUVL source candidate. CO_2 LPPs have demonstrated an increased in-band conversion efficiency (CE) when compared to the Nd:YAG, due in the main to reduced opacity effects [2]. Pulse shortening techniques of the CO_2 temporal profile have been reported [3] along with CE values of 3-4% [4], however theoretical modelling has shown the potential to improve this figure.

We outline research undertaken to optimise the CE in CO_2 laser produced Sn plasmas. We use a novel pulse shortening technique to vary the CO_2 pulse duration between 5 & 50 ns, by clipping the N_2 tail from the temporal profile. These shortened pulses are then incident on two Sn target types; solid Sn and a preformed Sn plasma. We have investigated the effect of changing various laser parameters; gas mixture and lens position on in-band emission centred on 13.5 nm. This talk will present our findings for the resultant CE's as the pulse duration of the CO_2 laser is varied, along with the delay of pumping the Sn plasma preformed by a Nd:YAG laser.

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Presenting Author

P52

Design and Analysis of Liquid Metal EUV Collector Mirrors Using the Zemax Ray Tracing Code

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Focusing 13.5 nm light requires mirrors that are essentially atomically flat. Maintaining this high level of finish in front of a hot, debris producing, tin plasma is proving extremely difficult for extreme-ultraviolet (EUV) source manufacturers.

Our solution is to apply a thin coating of a liquid metal to the inside of a solid collector mirror shell, as the surface of clean liquid metals is atomically flat. This liquid metal, a tin alloy, is chosen as a compromise between EUV collection efficiency and low melting point. In parallel with the experimental characterisation of simple liquid metal collector optics, we have used the commercial ray tracing package Zemax [1] to model, analyse and assist in the design of liquid metal based EUV collector systems. We will continue to use Zemax throughout this research to define optimal mirror shape and size for particular EUV sources and particular EUV output powers depending on the application. Here we present an overview of the modelling work to date.

[1] http://www.zemax.com/

Presenting Author

P53

Emission Spectroscopy from Laser-Produced Plasmas of Relevance to Source Development

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Recent emission spectra obtained from laser-produced plasmas of relevance to source development will be presented. The plasmas were created using a nanosecond, Nd:Yag laser pulse and the spectra were recorded using a high resolution, soft x-ray, Schwob-Fraenkel spectrometer. The 2400 lines/mm grating within the Schwob-Fraenkel spectrometer was used and a wavelength range of 2-4 nm was covered with a resolution of ~0.005 nm (FWHM).

Presenting Author

P54

Two Colour and Two Photon Ionization Processes in Intense Extreme UV and Optical Laser Fields

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The development of short wavelength Free Electron Laser facilities operating in the VUV [1], EUV [2] and X-ray [3] ranges signals a new era for the study laser matter interactions in intense fields where the photon energy is well above the first ionization threshold [4]. In this case inner shell electrons in atoms, molecules and solids can play and important role in photoionization processes. In addition, the primacy of the photon over 'laser field effects' is reasserted in intense laser-matter interactions. This is true even at quite high irradiances (at and even beyond 10 TW cm^{-2}), although, with effort, non-linear photoionization processes may be induced [5].

In this talk I will introduce the Self Amplified Spontaneous Emission (SASE) FEL concept and briefly summarize some of our results from photoionization of rare gas atoms in intense EUV laser fields. The focus will be on two-photon excitation [6] and ionization [7] processes. Time permitting I will describe an EUV-NIR cross-correlation experiment, where the jitter between each laser field can be determined on a femtosecond timescale, will be highlighted [8,9]. A proposal to measure the duration of few-femtosecond and sub-femtosecond duration X-ray pulses at the LCLS will be outlined.

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