2011 International Workshop on EUV and Soft X-Ray Sources

November 7-10, 2011

Dublin ▪ Ireland

Workshop Abstracts

EUV Litho, Inc.

Contents

Organized by:

FIRE
Fluid, Ions and Radiation Ensemble in Integrated Plasma Modeling

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SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

EUV Litho, Inc.

Welcome

Dear Colleagues;

I will like to welcome you to the 2011 International Workshop on EUV and Soft X-Ray Sources in Dublin, Ireland.

This 3annual 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) and EUV Litho, Inc. and is supported by European Union through the Marie Curie IAPP project FIRE. 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, 2011 International Workshop on EUV and oft X-Ray 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)
Vladimir Borisov (Triniti)
John Costello (DCU)
Samir Ellwi (Adlyte)
Akira Endo (Waseda University)
Henryk Fiedorowicz (Military University of Technology, Poland)
Torsten Feigl (IOF-Fraunhofer)
Francesco Flora (ENEA)
Debbie Gustafson (Energetiq)
Ahmed Hassanein (Purdue)
Takeshi Higashiguchi (Utsunomia University)
Larissa Juschkin (Aachen University)
Hiroo Kinoshita (Hyogo University)
Chiew-seng Koay (IBM)
Konstantin Koshelev (ISAN)
Rainer Lebert (Bruker)
Peter Loosen (ILT-Fraunhofer)
Eric Louis (FOM)
James Lunney (Trinity College, Dublin)
John Madey (University of Hawaii)
Alan Michette (King's College London)
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)
Martin Richardson (UCF)
Valentino Rigato (INFN-LNL)
Jorge Rocca (University of Colorado)
David Ruzic (University of Illinois)
Akira Sasaki (JAEA)
Leonid Shmaenok (PhysTex)
Menachem Shoval (Intel)
Emma Sokell (UCD)
Harun Solak (PSI)
Seichi Tagawa (Osaka University)
Mark Tillack (UC San Diego)
Andrei Yakunin (ASML)
Hironari Yamada (PPL)
Sergey Zakharov (Nano-UV / EPPRA)
Vivek Bakshi (EUV Litho, Inc.) - Organizing Chair
Padraig Dunne (UCD) - Organizing Co-Chair

Workshop Agenda

Agenda Outline

Monday, November 7, 2011

Location: Newman House, Stephen's Green, Dublin

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

Tuesday, November 8, 2011

Location: Astra Hall (Student Union Building), UCD Campus, Dublin

8:00 AM	Pickup at the Hotel (Stephen's Green and Burlington)
8:30 AM – 11:30 AM	Workshop Presentations
11:30 AM -12:30 PM	Lunch
1:00 PM – 4:30 PM	Workshop Presentations
5:30 PM – 7:00 PM	Poster Session and Reception
7:00 PM	Depart for Off-Site Dinner (Pickup at Astra Hall)

Wednesday, November 9, 2011

**Location: Astra Hall (Student Union Building),
UCD Campus, Dublin**

8:00 AM	Pickup at the Hotel (Stephen's Green and Burlington)
8:30 AM – 12:35 PM	Workshop Presentations
12:35 PM - 1:35 PM	Lunch
1:35 PM - 3:20 PM	Workshop Presentations
3:30 PM	Depart for tour of Dublin Castle (Pickup at Astra Hall)

Thursday, November 10, 2011

Location: Newman House, Stephen's Green, Dublin

Technical Working Group (TWG) Meeting

8:30 AM	Breakfast
9:00 AM – 10:00 AM	TWG Meeting

WORKSHOP AGENDA

2011 International Workshop on EUV and Soft X-Ray Sources

November 7-10, 2011, Dublin, Ireland

Monday, November 7, 2011 (Newman House)

5:00 PM – 7:00 PM Reception and Registration

Tuesday, November 8, 2011 (Astra Hall)

8:30 AM Welcome and Announcements

Introduction and Announcements (Intro-1)
Vivek Bakshi, EUV Litho, Inc., USA

8:35 AM Plenary Talk

Current Status and Future of EUV and BEUV Sources (S9)
Konstantin Koshelev, ISAN, Russia

9:05 AM Session 1: 6.x nm BEUV Sources

Recent Progress of Beyond EUV (BEUV) Sources (S40) (Invited)
Takeshi Higashiguchi, Utsunomiya University, Japan
Conversion Efficiency of 6.X nm Emitted From Nd: YAG and CO2 Laser Produced Plasma (S29)
Shinsuke Fujioka, Osaka University, Japan
Experimental and Theoretical Studies of Gd and Tb radiation in 6.X spectral Region (S35) (Invited)
Vladimir Krivtsun, ISAN, Russia

9:55 AM Break (15 Minutes)

10:10 AM Session 2: 13.5 nm EUV Sources for HVM

20 minute presentations

EUV Lithography and EUV Sources (S8) (Invited)
Vadim Banine, ASML

EUV Lithography Light Source Power Scaling in Practice - LDP Source Development at XTREME Technologies (S45) (Invited)
Harald Verbraak, Xtreme Technologies, Germany

Physical Aspects of Pre-pulsed Tin Micro Droplet in Transport Magnetic Field (S19) (Invited)
Akira Endo, Waseda University, Japan

Ionization Dynamics in the Laser Plasma in Gases and a Possible Way for Optimization of the EUV Source (S25)
Serguei Kalmykov, Ioffe Physical-Technical Institute, Russia
Towards 20kW CO_2 Laser System for Sn-LPP EUV source – Recent Developments (S38)
Krzysztof M Nowak, Gigaphoton, Japan

11:30 AM LUNCH (60 Minutes)

12:30 PM Session 3: EUV Sources for EUV Metrology

20 minute Presentations

A Novel High Average Power High Brightness Soft X-ray Source Using a Thin Disk Laser System for Optimized Laser Produced Plasma Generation (S30) (Invited)
Ioanna Mantouvalou, Max-Born Institute, Germany
High brightness EUV source for EUVL applications (S32) (Invited)
Oran Morris, Adlyte, Switzerland

High Brightness EUV Light Source for Actinic Inspection & Microscopy (S43) (Invited)
Sergey V. Zakharov, NanoUV, France

High brightness Electrodeless Z-Pinch^{TM} EUV Source for Mask Inspection Tools (S46) (Invited)
Deborah Gustafson, Energetiq, USA
High Brightness Source Collector Module for EUV Metrology (S51)
Ken Fahey, NewLambda Technologies, Ireland

2:10 PM Break (15 Minutes)

2:25 PM Session 4: FIRE SESSION (Modeling)

20 minute presentations

Non-LTE Plasma Modeling with Cretin (S55) (Invited)
Howard Scott, LLNL, USA

Modeling of "Mist Target" – the Ideal Target for LPP Source (S33)
Vladimir Ivanov, ISAN, Russia

Peculiarities of Modeling LPP Source at 6.X nm (S36) (Invited)
Vladimir Novikov, ISAN, Russia

Benchmarking Atomic Processes and Atomic Spectra for the Modeling of EUV Sources (S13)
Akira Sasaki, JAEA, Japan

Plasma Source Modeling for Future Lithography at 6.7 nm and Other Applications (S18)
Gerry O'Sullivan, UCD, Ireland

Properties of High Intensity Radiation Plasma Sources (S44) (Invited)
Sergey V. Zakharov, EPPRA and NanoUV, France

4:25 PM Session 5: Alternative Concepts for EUV Sources

15 Minute Presentations

A Kilowatt-scale Free Electron Laser Driven by L-band Superconducting Linear Accelerator Operating in a Burst Mode (S15) (Invited)
Mikhail Yurkov, DESY, Germany

Project of Acceleration Complex for Extreme Ultraviolet Nanolithography Based on a Free Electron Laser (S27)
E. M. Syresin, Joint Institute for Nuclear Research, Russia
Pushing the Limits of Laser Synchrotron Light Sources (S12) (Invited)
Igor Pogorelsky, BNL, USA

A Rotamak EUV Source (S20)
Masami Ohnishi, Kansai University, Japan

5:30 PM – 7:00 PM Session 6: Poster Session

7:00 PM Depart for Dinner

End of Day 2

5:30 PM Session 6: Poster Session

Topic: HVM Sources

1) Time Resolved EUV Spectra of Laser Produced Tin Plasmas (S59)
Paddy Haydon, DCU, Ireland

2) Diagnostics Tools for EUV and BEUV Radiating Plasmas (S37)
A. Lash, ISAN, Russia

3) Investigation of spatial and spectral characteristics of EUV emission from Laser Assisted Vacuum Arc (S53)
Isaac Tobin, Trinity College Dublin, Ireland

Topic: 6.x nm BEUV Sources

4) Basic Research on 6.x nm EUV Generation by Laser Produced Plasma (S26)
Tsukasa Hori, Gigaphoton, Japan

5) Spectral Analysis of EUV Emissions from Lanthanide Metal Atomic Ions in Large Helical Devices (LHD) Plasmas (S31)
Fumihiro Koike, Kitasato University, Japan

6) Extreme Ultraviolet Source at 6.7 nm Based on a Low-density Plasma (S41)
Takamitsu Otsuka, Utsunomiya University, Japan

7) Investigating the Effects of Laser Power Density and Pulse Duration on the 6.7-nm BEUV Emission (S48)
Thomas Cummins, UCD, Ireland

8) The Effect of Viewing Angle on EUV Spectra of Laser Produced Gadolinium Plasmas (S49)
Colm O'Gorman, UCD, Ireland

Topic: EUV Sources for Metrology

9) Development of Novel EUV Source Collector Module Using a Tin Based Liquid Metal Alloy (S50)
Paul Sheriden, NewLambda Technologies, Ireland

Topic: Modeling

10) Radiance of Non-equilibrium Gd Plasma (S42)
Vasily S. Zakharov, EPPRA, France

Topic: Alternative Concepts /Non-EUVL Applications of EUV Sources

11) First Demonstration of Pump and Probe Experiment for Wide-gap Semiconductors Using Free Electron Laser and Synchronously-operated Femtosecond Laser (S22)
Nobuhiko Sarukura, Osaka University, Japan

12) The Anisotropy of the EUV Radiation from the Plasma of the High-current Pulse Plasma Diode (S23)
Ievgeniia Borgun, Kharkov National University, Ukraine

13) Development of a 10μm Optical Storage Cavity (S28)
Kazuyuki Sakaue, Waseda University, Japan

14) Radiation Sources in the Extreme Ultraviolet and Soft X-ray Region (S52)
Deirdre Kilbane, UCD, Ireland

Wednesday, November 9, 2011

8:30 AM Announcements

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

8:35 AM Keynote Presentations

SFI - Promoting Science in Ireland (S2)
Graeme Horley, SFI, Ireland

IAPP Program Review (S1)
Laura Apostol, IAPP, EU

9:35 AM Session 7: Business Presentations

15 Minute Presentations

Foreign Direct Investment (S5)
Donald Flavin, IDA, Ireland

Innovation – The 3rd Pillar at University College Dublin (S7)
Peter Clinch, UCD

10:20 AM Break (15 Minutes)

10:35 AM Session 8: Multilayer Optics

20 Minute Presentations

Multilayer Mirrors for Free Electron Laser Applications (S21) (Invited)
Sasa Bajt, DESY

Corrosion-resistant Multilayer Coatings for the 28-50 nm Wavelength Region (S17) (Invited)

Regina Soufli, LLNL, USA

Multilayer Development for Extreme Ultraviolet and Shorter Wavelength Lithography (S24) (Invited)
Eric Louis, FOM, Netherlands

Multilayer Design for EUV lithography (S39)
M.G. Pelizzo, LUXOR CNR, Italy
Multilayer Coating for EUV Collector Mirrors (S16) (Invited)
Hagen Pauer, Fraunhofer, Germany

Multilayers for Present and Future Generations of EUVL (S56) (Invited)
Yuriy Platonov, RIT, USA

12:35 PM Lunch (60 Minutes)

1:35 PM Session 9: Soft X-Ray Sources for Non-Semiconductor Applications

20 Minute Presentations

EUV Microscopy - a User's Perspective (S57)
Dimitri Scholz, UCD, Ireland

Demonstration of a High-brightness Water-window Laser-plasma Source for Soft x-ray microscopy (S20)
Dale Martz, KTH, Sweden
Soft X-ray Source Development at Energetiq Technology (S47)
Deborah Gustafson, Energetiq, USA

The EUV Laser Program at the University of Bern: Bridging the Gap between Tools and Applications (S11)
Davide Bleiner, University of Bern

Light for the Nano-world (S54)
Larissa Juschkin, RWTH-TOS (Germany)

3:10 PM Workshop Summary and Announcements

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

3:30 PM Workshop Adjourned (Leave for Tour of Dublin Castle)

Thursday, November 10, 2011

Location: Newman House, Stephen's Green, Dublin

Technical Working Group (TWG) Meeting

8:30 AM	Breakfast
9:00 AM – 10:00 AM	TWG Meeting

Abstracts

S1

INDUSTRY-ACADEMIA PARTNERSHIPS AND PATHWAYS (IAPP) Program Review

Laura Apostol

European Commission - Research Executive Agency (REA)

This keynote talk will give an overview of the IAPP Program. Objective of this action is to seek to enhance industry-academia cooperation in terms of research training, career development and knowledge sharing, in particular with SMEs, and including traditional manufacturing industries. It is based on longer term cooperation programs with a high potential for increasing mutual understanding of the different cultural settings and skill requirements of both the industrial and academic sectors. The IAPP action supports the 'Innovation Union' flagship initiative by strengthening research and business performance and by promoting innovation and knowledge transfer throughout the EU. Stronger cooperation between universities and business via staff exchange will encourage entrepreneurship and help to turn creative ideas into innovative products and processes that can efficiently address European and global societal challenges.

Presenting Author

Laura Apostol was born in Buzau (Romania). She studied Engineering Sciences at the University Polytechnic from Bucharest where she completed the diploma in Hydraulic Machines, in 1991. In 2000 she started working on her MSc and obtained her MSc in 2002 in management and business administration at the same university. She was starting to work in the Ministry of Education and Research in 1992 as an expert. From 1994 she was working at the Romanian National University Research Council, first as World Bank Program Manager, then as Head of the Research Funding Department. She was involved in implementation of the Reform for Higher Education and Research in Romania, in settle of monitoring, evaluation and audit procedures and methodologies of the research grants, in distribution of the budgetary founds for research, in impact assessment of the World Bank Loan for Higher Education and Research Reform Project In September 2003 she was delegated to the European Commission as detached national expert. She was Project Officer dealing with the different Panels within the framework of the Directorate-General for Research, the Unit for Marie Curie Fellowships (Improving Human Potential Program). From 2010 she is Program Officer dealing with Mathematics and Physics Panel within Marie Curie Host Fellowships Unit in the Research Executive Agency – REA.

S2

SFI - Promoting Science in Ireland

Aisling McEvoy

SFI, Ireland

Science Foundation Ireland's Information, Communications and Emergent Technologies (IC&ET) Directorate is responsible for the overseeing one of the three key areas of SFI's broad scientific remit. Currently, the Directorate is responsible for approximately 400 active research awards that encompass a very diverse range of interests, including computer sciences (both hardware and software), optics and communications, physical sciences, mathematics, engineering, and beyond. This presentation give some background to SFI's work and some of its achievements to date, and will also exhibit some of the key research being currently carried out under this Directorate.

Presenting Author

S3

Foreign Direct Investment in Information and Communication Technologies

Donal Flavin

Information and Communication Technologies Division, IDA, Ireland

This presentation will cover recent ICT investments in Ireland, the reasons why companies are investing in Ireland and the key attributes that Ireland has to offer to new investors. IDA Ireland is Ireland's inward investment agency. IDA Ireland partners with foreign investors, helping them set up and develop in Ireland.

Presenting Author

Donal Flavin is Vice President, Information & Communication Technologies Division (ICT), IDA, Ireland. He has responsibility for greenfield ICT investments from the US. Prior to his current position, Donal was IDA Regional Executive in Galway, where he had responsibility for new investments in the West and Mid West of Ireland. Donal holds an agri-business degree and MBA from University College Dublin (UCD).

S7

Innovation – The 3rd Pillar at University College Dublin

J. Peter Clinch, PhD

NovaUCD, Belfield Innovation Park
University College Dublin, Ireland

Innovation is a key driver of productivity growth and economic development and a key contributor to social and cultural development. Innovation now resides alongside research and teaching and learning as the third pillar of UCD's core mission of service to Ireland and the wider world. Our objective is to link education, research and innovation more effectively in order to increase the conversion and translation of knowledge, ideas, and inventions into life enhancing products, services and policies. In this regard the University actively supports researchers and students, at all stages, who are commercialising their research outputs and in developing their entrepreneurial attributes.

Presenting Author

Professor J. Peter Clinch is University College Dublin's Vice-President for Innovation. Professor Clinch holds the Jean Monnet Professorship of Economic Integration (European Environmental Policy) and is UCD Professor of Planning. In addition to a strong academic record, he has held visiting positions at the University of California, Berkeley and San Diego and has carried out work for the World Bank, OECD and UK Overseas Development Administration. As Special Adviser to the Government from 2008 to 2011 he was influential in drafting *Building Ireland's Smart Economy* and in the creation of both the National Innovation Taskforce and Innovation Fund Ireland. Peter's considerable experience of working in government includes working in partnership with senior civil servants as well as some of the leading companies in the world.

In addition to serving, *inter alia*, Cabinet Committees on Economic Renewal, Climate Change and Energy Security, and Science, Technology and Innovation, he participated in bilaterals between the Prime Minister and Ministers and was a member of Irish Government delegations to the European Council, the UN General Assembly, Davos World Economic Forum, Asia-Europe Meetings, a series of overseas trade missions, as well as the Taoiseach's (Prime-Ministerial) delegations to meet Heads of States, including US President Obama and Chinese Premier Wen Jibao.

Professor Clinch is also the co-founder of a UCD spin-out company AP EnvEcon Ltd.

S8

EUV Lithography and EUVL Sources

Vadim Banine

ASML, Netherlands

Presenting Author

Dr. Vadim Banine is currently Director of Research at ASML. He has worked for ASML since 1996 and has held positions of Senior Research Manager, Head of ASML laboratory and external project co-ordinator for ASML research department. He received his PhD in 1994 from Eindhoven University of Technology, The Netherlands (TUE). The subject of his PhD work was the diagnostics of combustion plasma. From 1995-96 he did his postdoctoral work at TUE in the Laboratory of Heat and Mass Transfer. He has over 40 publications and over 100 patens. He is also the winner of ASML patent award.

S9

Current Status and Future of EUV and BEUV Sources

Konstantin N. Koshelev

ISAN, RnD ISAN, Troitsk, Moscow district, Russia

13.5 nm source with HVM characteristics is still a key challenge for EUV Lithography. Both technologies – LPP and DPP (LDP) – are demonstrating serious progress but also need essential performance improvement. We report results of experimental and theoretical investigations of EUV source physics, discuss expected fundamental limitations for DPP and LPP and describe possible ways to improve source characteristics.

Presenting Author

Konstantin N. Koshelev is the president of RnD-ISAN and a leading scientific specialist in plasma physics and atomic spectroscopy. He was invited professor at Pierre and Marie Curie University (1991), Orsay University (1992) and Auburn University (1990 and 1995).

S11

The EUV Laser Program at the University of Bern: Bridging the Gap between Tools and Applications

D. Bleiner, J.E. Balmer, F. Staub, F. Jia, L. Masoudnia, M. Ruiz-Lopez

Institute for Applied Physics, University of Berne, Berne, Switzerland

The University of Bern has a long tradition in the field of lasers, started shortly after their invention 50 years ago. A Terawatt IR laser system, called "*BeAGLE*", is in operation for igniting hot and dense plasmas, as the amplification medium for EUV/soft X-ray laser radiation. Such a lab-scale short-wavelength laser has unique characteristics of temporal coherence (Dl/l < 0.01%) and photon count (> 10^{11} ph/shot) that are unmatched by any other source. The research activity at the University of Bern in the field of short-wavelength radiation is further expanding with two teams, one team focusing on the development of the source, and one team focusing on the applications. The "*X-ray laser physics*" group is focused on the *down-scaling* of the lasing wavelength, and the *up-scaling* of the repetition rate. Successful experiments have been reported on the saturated laser emission of Pd (λ=14.7 nm), Ag (13.9 nm), In (12.6 nm), Sn (12 nm), Sb (11.4 nm), Ba (9.2 nm). Ongoing experiments on La (8.8 nm) and Sm (7.4 nm) are profiting from original driver focusing ("TGRIP") and target concepts (coated targets, hollow targets). High repetition rate is planned using an *optical parametric – chirped pulse amplification* architecture, where there is no concern about heat-removal due to the conversion approach based on mere optical energy. The "*EUV plasma radiation*" group is leveraging its research on plasma fundamentals as well as the unique characteristics of our source for high-contrast imaging, EUV microscopy, rapid mask defect inspection, high-resolution spectroscopy, photoemission, and others. In this presentation, the various aspect of our EUV laser program will be addressed, and a roadmap for forthcoming activities will be provided.

Presenting Author

Dr. Davide Bleiner is XUV Laser Scientist at the Institute for Applied Physics of the University of Berne. He obtained his PhD in 2002 from the Swiss Federal Institute of Technology (ETH) in Zurich, working on laser ablation for inductively coupled plasma (ICP) mass spectrometry. He has earned research fellowships from the Flemish Science Foundation for computational investigation of laser plasma, from the Swiss Science Foundation for instrumental design and the Italian Research Council for laser plasma ion implantation. He was awarded the Elsevier Atomic Spectrometry Award in 2005. His activity is mostly focused on the design and implementation of instrumentation for improved laser plasma sources, either ion or photon-based. Lately he is focused on EUV laser for actinic nano-imaging and photoelectron spectroscopy. He acts as a reviewer for a number of international journals in atomic spectrometry and laser science.

S12

Pushing the Limits of Laser Synchrotron Light Sources

I. V. Pogorelsky

Accelerator Test Facility, Brookhaven National Laboratory, Upton, NY, USA

We review recent progress in developing a high-brightness laser synchrotron x-ray source based on Compton scattering between a picosecond CO_2 laser and, matched to it, counter-propagating electron beam. This scheme provides the maximum radiation yield in excess of one x-ray photon per electron. High-brightness capability of the electron linear accelerator converts into the spectral brightness of the produced x-rays. We analyze factors that contribute to improved coherence of Compton x-rays and enable single-shot high-contrast radiography.

Proposed placement of the Compton interaction point inside a laser cavity shall enable laser synchrotron sources of high average power compatible with demands of next-generation lithography

Presenting Author

S13

Benchmarking Atomic Processes and Atomic Spectra for the Modeling of EUV Sources

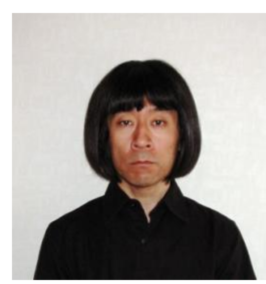
Akira Sasaki

Quantum Beam Science Directorate, Japan Atomic Energy Agency, Japan

Although the successful development of the light source in the 13.5nm wavelength region, still higher source power and efficiency are desired for the EUV lithography. Furthermore, future lithography demands light sources at shorter wavelength. The atomic model of Sn to Gd/Tb plasmas is useful for predicting the emission spectra and conversion efficiency, however the model also needs improvements in terms of the accuracy of calculation from wavelengths of the emission lines to the coefficient of radiative transfer. Benchmarking the atomic model is not trivial because of the complex atomic structure as well as emission spectrum of multiple charged ions. We show the validation of the atomic model based on systematic comparison of calculated and experimental emission spectra. As an example, the charge state distribution and level population, for which best agreement with measured XUV spectra from Kr plasma is discussed. Possible comparison between calculated results from different atomic codes is also discussed.

Presenting Author

Akira Sasaki received the Dr. Eng. degree in energy science from Tokyo Institute of Technology, Tokyo, Japan in 1991. He joined Japan Atomic Energy Agency in 1996. He has been studying modeling and simulation of atomic processes of Xe and Sn plasmas of the EUV source for lithographic applications since 2002.



S14

Demonstration of a High-brightness Water-window Laser-Plasma Source for Soft X-ray Microscopy

D. H. Martz[1], O. von Hofsten[1], M. Selin[1], H. Legall[2], G. Blobel[2], C. Seim[3], M. Bertilson[1], H. Stiel[2], U. Vogt[1], and H. M. Hertz[1]

[1]Biomedical and X-Ray Physics, Dept. of Applied Physics, KTH Royal Inst. of Technology/Albanova, Stockholm, Sweden
[2]Max-Born-Institut, Max-Born-Straße Berlin, Germany
[3]Institute of Optics and Atomic Physics - Analytical X-ray physics, Technical University-Berlin, Berlin Germany

We report on the advancement of a laser plasma water-window light source for laboratory based soft x-ray microscopy. The source employs a 20 μm diameter liquid nitrogen jet as a non-contaminating regenerative target for soft x-ray generation at high pulse repetition rates. An increase of photon flux to 7 x 10^{14} photons / (s * sr * line) centered at 2.48 nm measured by a slit-grating spectrometer is shown. The source size was measured using a normal incidence concave soft x-ray mirror, giving an average brilliance of 10^{12} photons / (s * sr * μm^2 * line). To our knowledge, this advancement demonstrates the highest average brightness for a table-top soft x-ray water-window source to date. Depending on the collection scheme, the source allows for greater than 10^7 photons / (s * μm^2) at the sample position enabling image collection in the sub 10-30 sec range. These results demonstrate the possibility of obtaining table-top water-window microscopic images in the laboratory which will be comparable to those taken at synchrotron facilities.

Presenting Author

Dr. Dale Martz is a Post Doctoral Fellow at KTH - Royal Institute of Technology in Stockholm Sweden. Over the past seven years he has worked with the development of EUV/Soft X-Ray lasers and light sources. He received his Ph.D. at Colorado State University from the Engineering Research Center for EUV Science and Technology. He has worked with both gas discharge and laser driven short wavelength sources for applications ranging from imaging and lithography to spectroscopy and laser metrology. The current focus of his research is to advanced table-top liquid jet water-window high power light sources for tomographic imaging of biological samples in the X-Ray Biophysics research group at KTH.

S15

A kilowatt-scale Free Electron Laser Driven by L-band Superconducting Linear Accelerator Operating in a Burst Mode

E.A. Schneidmiller, V.F. Vogel, H. Weise, M.V. Yurkov

Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

The driving engine of the Free Electron Laser in Hamburg (FLASH) is an L-band superconducting accelerator operating in a burst mode with 800 microsecond pulse duration at a repetition rate of 10 Hz. FLASH technology holds great potential for increasing the average power of the linear accelerator and an increase of the conversion efficiency of the electron kinetic energy to the light. We present a concept of FLASH like free electron laser capable to operate in 13.x nm and 6.x nm wavelength bands with an average power up to 3 kW.

Presenting Author

S16

Multilayer Coating for EUV Collector Mirrors

Hagen Pauer, Marco Perske, Sergiy Yulin, Marcus Trost, Sven Schröder, Angela Duparré, Torsten Feigl, Norbert Kaiser

Fraunhofer-Institut für Angewandte Optik und Feinmechanik, Albert-Einstein-Str. 7, 07745 Jena, Germany

Bringing EUV Lithography forward to high volume manufacturing, one of the main challenges to date is to deliver a high level of EUV power to the 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.
For this type of EUV source, ellipsoidal collector mirrors have to be coated with a highly reflective, laterally graded multilayer to achieve a consistently high reflectance of more than 65% at a wavelength of (13.50 ± 0.03) nm over the entire surface. The multilayer deposition of such collectors with a diameter of 660 mm still poses one of the biggest challenges with respect to quality, accuracy and lifetime.

Furthermore, the collector surface finish has to be controlled in terms of high spatial frequency roughness in order to verify the specified surface roughness of less than 0.2 nm (rms). Moreover, the EUV performance can be predicted using scatter models based on the optical and roughness properties. For a thorough surface characterization of EUV collector mirror substrates, a new scatterometer (ALBATROSS) has been developed at Fraunhofer IOF together with a novel analysis technique.

This paper presents technical advances in surface characterization methods by ALBATROSS and latest coating results of 5 sr collector mirrors for EUVL deposited by DC magnetron sputtering.

Presenting Author

Hagen Pauer received a B. Eng. degree in 2006 and the M. Eng. degree in 2009 both at the University of Applied Sciences in Jena, Germany. Since 2009 he works at the Fraunhofer Institute for Applied Optics and Precision Engineering as scientist and process engineer with main focus on EUV and X-ray optics.

S17

Corrosion-resistant Multilayer Coatings for the 28-50 nm Wavelength Region

Regina Soufli

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Magnesium/silicon carbide (Mg/SiC) has the potential to be one of the best-performing reflective multilayer coatings in the 28-50 nm wavelength range with applications in solar and plasma physics, spectroscopy, microscopy, and nano-patterning. Recent advances in tabletop EUV laser sources in this wavelength region enable the application of techniques that had been traditionally limited to large-scale facilities in smaller laboratories, and require highly efficient and stable multilayer coatings. Mg/SiC exhibits high reflectivity, near-zero stress, and excellent thermal stability and spectral selectivity compared to other candidate multilayer pairs. However, Mg/SiC has poor corrosion properties, exhibited as spots which sporadically develop and expand across the coating over time, completely degrading the reflective performance. This insidious problem has prevented Mg/SiC from being implemented in applications that require good lifetime stability. Although it is known that Mg is prone to corrosion after exposure to air and humidity, the exact mechanism of corrosion propagation in nanometer-scale Mg/SiC multilayers has not been studied, and there have not been any methods to prevent it. This talk will present a study of the origins of corrosion and the mechanisms of its propagation in Mg/SiC multilayers. Novel design concepts and experimental results will also be presented on corrosion-resistant Mg/SiC multilayers, aged for up to 3.5 years. Transmission and scanning electron microscopy, EUV reflectance and x-ray photoelectron spectroscopy measurements will be shown as part of this work.

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

Presenting Author

Regina Soufli received her Ph.D. in Electrical Engineering from the University of California, Berkeley, and was staff scientist at the Harvard-Smithsonian Center for Astrophysics working for NASA's Chandra X-ray Observatory. At Lawrence Livermore National Lab she has been principal investigator on EUV/x-ray optics programs for EUV lithography, solar physics, synchrotron and free-electron lasers, and high-energy physics. She has recently been working on x-ray optics for the Linac Coherent Light Source (LCLS), the world's first x-ray free electron laser, and on EUV multilayer optics for NASA/NOAA's space weather satellites and NASA's Solar Dynamics Observatory. Her interests are in EUV/x-ray interactions with matter, surface science, thin films, roughness and scattering. She is author of over 60 publications and a book chapter, and has received two "R&D 100" awards.

S18

Plasma Source Modeling for Future Lithography at 6.7 nm and Other Applications

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Tin plasmas are the brightest sources at 13.5 nm due to the presence of resonance 4p-4d and 4d-4f transitions in the spectra of ions from Sn^{8+} to Sn^{13+}. With increasing Z, these transitions move to shorter wavelength and overlap in adjacent ion stages to produce an intense unresolved transition array (UTA). In Gd (Z= 63) the UTA occurs near 6.7 nm. Plasmas containing gadolinium have been proposed as sources for next generation lithography at 6.x nm. To determine the optimum plasma conditions, atomic structure calculations have been performed for Gd^{11+} to Gd^{27+} ions. Compared to the spectrum of tin, it is shown that the width of the UTA is reduced, making the emission well matched to reflective optics which have a narrow bandpass. Plasma modeling calculations, assuming collisional-radiative equilibrium, showed that the optimum temperature for an optically thin plasma is close to 110 electron-volts. Maximum intensity occurs at 6.76 nm under these conditions and emission is dominated by transitions in palladium-like and silver-like ions.
At even higher Z, the UTA emits at shorter wavelengths though spin orbit splitting causes the emission of two distinct peaks the relative intensities of which are sensitive to ion stage distribution and hence plasma temperature.

Presenting Author

Prof. Gerry O'Sullivan obtained his PhD from University College Dublin (UCD) in 1980 for work on the spectroscopy of laser produced plasmas of medium to high Z elements that included the first observation the unresolved arrays now studied as emission sources for EUVL at 13.5 and 6.x nm, changes in their EUV emission due to opacity and the application of higher Z plasmas as sources of EUV continuum radiation. After a brief period at the University of Maryland and National Bureau of Standards he returned to Dublin where he was employed at Dublin City University from 1981 before moving to a lectureship at UCD in 1986. He is currently a Professor at UCD and served as Head of the School of Physics from 2002 -2008. His research interests include EUV and soft x-ray continuum generation from laser produced plasmas and application to inner shell photoabsorption studies of atoms, ions and molecules, investigation of unresolved transition arrays (UTA) and their application as high brightness EUV sources, determination of the electronic structure of medium and high Z ions and spatial and temporal characterisation of laser produced plasmas.

In recent years, aided primarily by funding from Science Foundation Ireland, this work has focussed strongly on studies relevant to the development of EUVL sources. He has published more than 110 papers and is a member of the editorial board of European Journal of Physics. He is a member of the Royal Irish Academy and a Fellow of the Institute of Physics.

S19

Physical Aspects of Pre-pulsed Tin Micro Droplet in Transport Magnetic Field

Akira Endo

Waseda University, Japan

Pre-pulsed liquid Tin droplet is dispersed into a bunch of nano-clusters and irradiated by ionizing laser into full ionization phase. Initially spherical plasma is guided in mirror magnet onto tin atom collectors. The physics in these processes is unique but not well analyzed. The tin ion beam stream is also of extreme high current. It is tried to make a guideline to understand the process physically, and indicate potential application as high current ion source.

Presenting Author

Professor Dr Akira Endo obtained Dr. degree from Tokyo Institute of Technology in 1981 from research on high power short pulse laser optimization. He joined in Extreme Laser Program in Solid State Physics, University of Tokyo and performed research on multi terawatt excimer laser for XUV source pumping. He was employed in laser division of Max Planck Institute for Biophysical Chemistry, Goettingen, Germany during 1988-1992 for basic study of petawatt laser concept. He was a research leader in METI project "femtosecond technology" and responsible for "laser-Compton X-ray source" during 1996-2002. He was then the research leader in the "EUVA" program during 2002-2009, and contributed to establish the CO_2 laser pumped Tin droplet LPP scheme. He was invited to Jena University as a Zeiss Professor during 2009-2010 for half year and to FZD research center in Dresden for another half year. He is now a guest Professor in Waseda University in Tokyo, Japan.

S20

A Rotamak EUV Source

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The rotamak has been shown to be a suitable EUV source. It is an electrode-less discharge produced plasma developed originally for fusion applications.

The rotamak plasma is sustained by means of a rotating magnetic field (RMF). This RMF penetrates into the plasma much further than the classical skin depth because of a unique nonlinear mechanism. This allows for a remarkably efficient coupling of the radio frequency power to the rotamak plasma. The geometry of the rotamak is relatively simple and the plasma is not completely surrounded by coils. This offers a clear, almost uninterrupted view of the plasma for the purpose of extracting the emitted radiation. The Xenon plasma discharge is sustained for a period of 5 ms, limited only by the available radio frequency oscillators The EUV radiation was detected using a Silicon photodiode with a directly deposited thin film filter. Up to 66 Watt of EUV radiation was measured in experiments using 200 kHz RMF to sustain a 3 cm rotamak. A smaller rotamak (3 mm) using 13.56 MHz RMF is being developed. Up to 10 Watt EUV radiation has been measured in recent preliminary experiments.

Presenting Author

S21

Multilayer Mirrors for Free Electron Laser Applications

S. Bajt

Photon Science, DESY, Hamburg, Germany

X-ray Free Electron Lasers (FELs) are tunable wavelength X-ray sources, operating from the EUV to hard X-rays. These sources produce extremely short and intense pulses of radiation, with peak powers in the GW, but average power of tens of Watts.

The first operational X-ray FEL, FLASH at DESY, operates over a range from 30 nm to the water window regime, at ~4.2 nm. This entire wavelength regime can utilize normal incidence mirrors based on reflective multilayer coatings. At some wavelengths, multi layer coatings have been perfected for EUVL applications, especially at 13.5 nm. For other wavelengths, especially shorter ones, the specifications for good quality multilayers are more demanding but with substantial effort the performance of mirrors in this regime are improving. In this talk some scientific applications of soft X-ray FELs in combination with newly developed multilayer--based optics will be presented, and the effects on optics by intense FEL beams will be discussed.

Presenting Author

Dr. Saša Bajt received her PhD in Physics at the University of Heidelberg in Germany. She worked for The University of Chicago at the National Synchrotron Light Source (NSLS) developing X-ray fluorescence microprobe analysis and micro X-ray spectroscopy. As a staff scientist at Lawrence Livermore National Laboratory in USA she led a team developing high reflectivity multilayer structures for EUVL and designed protective capping layers to extend their lifetime. Since 2008 Dr. Bajt is a group leader developing optics for X-ray FELs and other coherent X-ray sources and studying the damage of the coatings under extreme conditions. She is also active in utilizing synchrotron-based in infrared micro-spectroscopy to analyze samples brought back by NASA's Stardust mission.

S22

First Demonstration of Pump and Probe Experiment for Wide-gap Semiconductors Using Free Electron Laser and Synchronously-operated Femtosecond Laser

Nobuhiko Sarukura[1], Kohei Yamanoi[1], Kohei Sakai[1], Tomoharu Nakazato[1], Marilou Cadatal-Raduban[1], Toshihiko Shimizu[1], Masataka Kano[2], Akira Wakamiya[2], Tsuguo Fukuda[3], Mitsuru Nagasono[4], Tadashi Togashi[4, 5], Takahiro Sato[4], Atsushi Higashiya[4], Makina Yabashi[4], Tetsuya Ishikawa[4], Haruhiko Ohashi[4, 5], Hiroaki Kimura[4, 5]

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Pump-probe experiments of wide-gap semiconductors were accomplished for the first time using an extreme ultraviolet free electron laser (EUV-FEL) tuned at 60-nm wavelength and the third harmonics (266 nm) of a Ti: Sapphire laser synchronized with the EUV-FEL. Time-resolved fluorescence intensity measurements were performed by controlling the spatial overlap between beams from both sources using a streak camera system. This allows simultaneous measurement of both decay time and fluorescence intensity. In this work, the difference in the behavior of electrons in undoped and in impurity-doped ZnO crystals was successfully observed in terms of their decay time and fluorescence intensity. Our results suggest that X-ray free electron lasers (XFEL) or EUV-FEL facilities play important roles for the spectroscopy of solid targets including other wide-gap semiconductors such as GaN.

Presenting Author

S23

The Anisotropy of the EUV Radiation from the Plasma of the High-current Pulse Plasma Diode

Ievgeniia Borgun[1)], Mykola Azarenkov[1)], Ahmed Hassanein[2)], Alexander Tseluyko[1)], Valentine Lazurik[1)], Dmitry Ryabchikov[1)], Igor Sereda[1)],

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[2)] Purdue University, West Lafayette, USA

The strong anisotropy of the radiation with 13.5 nm wavelength in the high-current pulse plasma diode in tin vapor has been observed. The anisotropic radiation has been obtained as series of the intensive short (50-200 ns) pulses exceeding the background radiation with the same wavelength.

The anisotropy of radiation occurred when the applied discharge power exceeds certain level. (In our case this level corresponded to the capacitor bank energy more than 20 J). It has been shown that the ratio of the longitudinal intensity to the transverse intensity relatively to the discharge axis varies in the range of $j_{\parallel}/j_{\perp}$= 0.2…20 depending on the external conditions. This effect may considerably enhance an efficiency of the EUV radiation sources.

Presenting Author

S24

Multilayer Development for Extreme Ultraviolet and Shorter Wavelength Lithography

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[2]*Carl Zeiss SMT AG, Oberkochen, Germany*
[3] *MESA+ Institute for Nano Technology, University of Twente, The Netherlands*

Multilayer coatings form a key component of EUV optical systems. The research required to develop this class of optics is ongoing for several decades already.

In this presentation we will discuss the path from fundamental research on the deposition of layers of a few nm thickness only towards a fully developed process, matured to deposit optics for prototype lithography machines. Topics like multilayer deposition, smoothing of interfaces, thermal stability, interface engineering, multilayer induced stress, and lateral uniformity will be discussed and examples of multilayer coated optics that fulfil the extremely tight specifications of EUV lithography machines will be given. Furthermore, solutions to suppress parasitic longer wavelength radiation emitted by EUV sources will be discussed.

Yet, while the first EUV litho tools are being shipped to semiconductor manufacturers, research on multilayers for an even shorter wavelength of 6.x nm already takes place. This means other multilayer materials and, because of its increasing importance, even more focus on issues like smooth layer growth and prevention of intermixing.

Presenting Author

Eric Louis is a senior scientist at FOM Rijnhuizen (the Netherlands) where he is involved in research and development of soft X-ray and EUV multilayer reflective coatings since 1992. He worked on multilayers for several applications such as space research and synchrotron beam lines, but focused his research primarily on multilayers for EUV lithography. As leader of the group 'Advanced applications of XUV Optics', Eric Louis has been responsible for research, development and coating of various optics for EUV lithography.
The extensive know how developed for this application is the basis for the development of multilayer coated optics for XUV and soft X-ray free electron lasers.

S25

Ionization Dynamics in the Laser Plasma in Gases and a Possible Way for Optimization of the EUV Source

Viktor Belik, Serguei Kalmykov, Mikhail Petrenko, Maxim Sasin

Ioffe Physical-Technical Institute, St. Petersburg, Russia

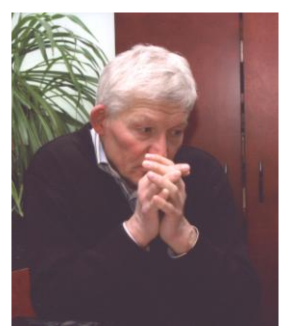
Estimations calculated for initiation of the laser plasma in the gas with an IR laser show that only a few of primary electrons can be produced due to the multiphotonic effect in neutral gas target. As the result, subsequent collisional ionization is delayed for a substantial portion of the laser pulse, and only at its end high-Z ions appear to emit EUV radiation. This leads to what the conversion efficiency (CE) is small and demonstrates a large scattering between different experiments.

On the contrary, being strongly dependent on the energy of laser radiation quanta, photoionization rates of UV excimer lasers are by many orders of magnitude higher than those of IR lasers. Thus, at intensity about 1 TW/cm^2 KrF laser radiation (λ = 248 nm) is capable to ionize all atoms of Xe target during several first nanoseconds of the pulse. On the other side, since collisional laser energy absorption and electron heating are proportional to λ^2, IR lasers are much more effective for further plasma heating and high-Z ionization.

An idea emerges to combine favourable features of both the lasers, and to realize fast and effective pre-ionization of the Xe target by means of the KrF excimer laser and then to heat and maintain the plasma with the aid of an IR laser. Gain in the EUV radiation energy is expected to surpass the addition expense of the laser energy, thus increasing CE.

Spectroscopical measurements in Ar and Xe laser plasmas carried out in the present work confirm the numerical estimations above: spectral lines of Ar^{3+} appear already after the middle of the Nd: YAG laser pulse.

Presenting Author



Serguei Kalmykov was born March 6, 1939 in Leningrad, Soviet Union, in 1962 graduated from the Polytechnical Institute (now St. Petersburg State Polythechnical University) and had been put in the research staff of the Ioffe Institute (St. Petersburg) where I continue working until now. Candidate of math sciences (physics/mathematics) degree from 1980 (this Russian scientific degree is approximately equivalent to PhD in Anglo-Saxon countries). Between 1962 and 2002 I was involved into the high temperature plasma and fusion area (general tokamak physics, magnetic confinement, transport processes) but then, in 2007, changed it for the laser plasma EUV source physics. Author/coauthor of approximately 60 scientific publications.

S26

Basic Research on 6.x nm EUV Generation by Laser Produced Plasma

Tsukasa Hori, Tatsuya Yanagida, Hitoshi Nagano, Yasunori Wada, Soumagne Georg, Junichi Fujimoto, Hakaru Mizoguchi

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6.x nm EUV light has a possibility to be used as light source for lithography process in semiconductor device manufacturing. Thus investigation has been started to get information to generate 6.x nm EUV. The basic research of 6.x nm EUV generation by Laser Produced Plasma (LPP) have been made with experiments in a LPP test rig build for 13.5 nm EUV light source development. The test rig has a target system in a vacuum vessel, drive laser system and metrology system for 6.x nm EUV light. The target system can set planer target of Gadolinium. 6.x nm EUV light is detected through La/B4C mirror as a spectrum band pass filter. LPP experiments have been done with various irradiation conditions with plate target. EUV energy around 6.x nm wavelength region was measured with changing irradiation laser parameters. The measurement results will be shown.

Presenting Author

S27

Project of Acceleration Complex for Extreme Ultraviolet Nanolithography Based on a Free Electron Laser

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The project is aimed at creating an acceleration complex based on the 0.7 GeV superconducting linear accelerator for the free electron laser (FEL) used for nano industry and above all for extreme ultraviolet lithography (EUVL) at the 13.5 nm wavelength with an average laser radiation power of 0.5 kW. In the context of implementation of the project, it is suggested that the development of a conceptual design for EUVL with resolutions of 22 and 16 nm (and below) using one FEL radiation source operating at a 13.5 nm wavelength and with an average kilowatt scale power simultaneously for several scanners.

Presenting Author

S28

Development of a 10μm Optical Storage Cavity

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We have been developing a 10um optical storage cavity for laser-Compton EUV source at Waseda University. The test stand has been launched in order to evaluate 10um optical storage. Using 10W CO_2 laser and 2000 finesse cavity, it will be reached more than 1kW power inside the cavity. This situation can be useful for analyzing the thermal deformation of the optics. We will report recent progresses of 10um optical storage cavity and future prospective in this conference.

Presenting Author

Kazuyuki Sakaue is Assistant Professor of Applied physics department at Waseda University. He received a Ph. D degree in Accelerator Science from Waseda University. He has been active in the area of electron accelerators and laser-beam interactions for over 8 years. His current research involves study of high quality electron beam generation and the laser enhancement super-cavity system for upgrading the laser-beam interactions.

S29

Conversion Efficiency of 6.X nm Emitted From Nd:YAG and CO_2 Laser Produced Plasmas

Shinsuke Fujioka[1], Hiroaki Nishimura[1], Makazu Miyake[2], Teruyuki Ugomori[1], Minoru Yoshida[2], Hiroshi Azechi[1]

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6.X light source with high conversion efficiency and cleanness should be developed to extend capability of extreme ultraviolet lithography for semiconductor device fabrication. We have developed a calorimeter applicable to the wavelength range from 6.2 to 7.2 nm. This calorimeter consists of two Co/C multilayer mirrors and photodiode [1]. Energy conversion efficiencies from Nd:YAG and CO_2 lasers to 6.X nm light has been measured for Gd plasmas by using the calorimeter with consideration of angular distribution of 6.X nm light emission. The opacity of a Gd plasma affects 6.7 light generation [1,2], namely conversion efficiency and angular distribution, however, the opacity effect in a Gd-based 6.7 nm light source is relatively small compared to that on a Sn-based 13.5 nm source. Details of the experimental result will be presented.

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[2] T. Otsuka et al., Appl. Phys. Lett., Vol. 97, 111503 (2010).
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Presenting Author

S30

A Novel High Average Power High Brightness Soft X-ray Source Using a Thin Disk Laser System for Optimized Laser Produced Plasma Generation

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Berlin Laboratory for innovative X-ray technologies (BLiX)

For applications in soft x-ray spectroscopy, nano-scale imaging or extreme ultraviolet (EUV) metrology there are two basic source requirements: a high spectral brightness and a high average photon flux. Whereas the spectral brightness of the source is directly linked to spatial and/or spectral resolution the high average photon flux is responsible for short data acquisition times e.g. in soft x-ray analytics or EUV metrology. Laser based plasma (LPP) sources are well suited as soft x-ray sources for applications described above. However, to meet both demands high brightness and high average power dedicated optimized pump laser systems are required.

We present here novel compact, high average power, high spectral brightness soft x ray sources based on a thin disk laser pump system. In order to meet the special requirements for an optimized soft x-ray output we have modified a commercial high average power Yb:YAG – disk laser system (TRUMPF Laser Technology) using a diode-laser with variable pulse duration as seed for an regenerative amplifier. This Distributed Bragg Reflector (DBR) seed-diode has been developed in a cooperation with the Ferdinand-Braun-Institute, Berlin, and PicoLas GmbH, Aachen. After amplification of the seed pulse the whole system delivers 240 mJ laser pulses with 1 ns pulse duration and repetition rates of 100 – 200 Hz with an intensity variation of <2% and an M2-value of < 1.1. Due to the good beam quality focal spot sizes on the target in the order of 10 µm diameter are feasible leading to intensities up to 5x1014 W/cm2.

We have used the thin disk laser system in two different LPP setups at Berlin Laboratory for innovative X-ray technologies (BLiX). A rotating metal cylinder target system has been developed for spectroscopic purposes yielding line and background emission between 100 eV and 1200 eV. For experiments requiring a line emission in the water window such as x-ray microscopy a liquid nitrogen jet-system has been applied. Characteristics of the laser system as well as the two LPP setups will be discussed as well as first applications with both LPP systems will be presented.

Presenting Author

Dr. Ioanna Mantouvalou is affiliated with Technical University of Berlin. She works in the research group ‘analytical X-ray Physics’ , Institute for Optics and Atomic Physics, Berlin, Germany. In April 2005 she received diploma in Physics at the TU Berlin. Since October 2009 she has held Post Doc position at the TU Berlin, in the research groups ‘Analytical X-ray physics’ and ‘BLiX – Berlin laboratory for innovative X-ray technologies’ – involved in the development of a laser-produced plasma source for the soft X-ray region.

S31

Spectral Analysis of EUV Emissions from Lanthanide Metal Atomic Ions in Large Helical Device (LHD) Plasmas

Fumihiro Koike*[1], Izumi Murakami[#], Chihiro Suzuki[#], Naoki Tamura[#], Shigeru Sudo[#], Daiji Kato[#], Hiroyuki Sakaue[#], Shigeru Morita[#], Motoshi Goto[#], Takako Kato[#], Akira Sasaki[$]

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[$]Japan Atomic Energy Agency, Japan

To develop the shorter wavelength light source, we are suggested to investigate the heavier elements such as lanthanides. The wavelengths of the 4d - 4f transitions are reported to be, for example, 7.9 nm for Nd (Z=60), 7.0 nm for Eu (Z=63) , and 6.8 nm for Gd (Z=64) [1]. Recently, the 4d-4f transitions of Tb at 6.5 nm has been investigated theoretically by Sasaki et al [2].

Recently, emission spectra at around 6 ~ 7 nm range from Gd and Nd atomic ions have been measured using LHD (Large Helical Device) in NIFS (National Institute for Fusion Science, Japan). A Gd or Nd pellet has been injected into the plasma with the central electron temperature 2 ~ 3 keV, and the emission lines from Gd or Nd 4d open-shell ions has been observed. Those lines have been analyzed and compared to the presently carried out atomic structure calculations. Theoretical calculation has been performed using a group of computer codes GRASP92 [3], RATIP [4], and GRASP2K [5].

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Presenting Author

S32

High Brightness EUV Source for EUVL Applications

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At the Laboratory for Energy Conversion of ETH Zurich a fully operational continuous-running multi-kHz LPP light source has been developed over the last 5 years and is now undergoing system optimization. Adlyte, a spin-off of ETH Zurich, is working with industry leaders to commercialize the LPP source developed at ETH.

Absolute intensity measurements of the EUV radiation, formed using a droplet target, have been recorded. Measurements were recorded over 2π steradian with respect to the plasma. The droplet generator, a fully in-house developed system, was synchronized with an Nd:YAG laser for a range of operating frequencies. The laser pulse was focused to a power density of approximately 10^{11} W/cm^2 to maximize in-band emission. The EUV detector employed was a calibrated energy monitor. To complement the EUV measurements, out-of-band measurements were simultaneously recorded with a calibrated spectrometer in the wavelength range of 250 to 1000 nm.

Presenting Author

Oran Morris is a postdoctoral researcher at the Applied Laser Plasma Science (ALPS) facility in the Laboratory for Energy Conversion, ETH Zurich. He received his PhD from University College Dublin for research conducted in the Atomic, Molecular and Plasma Physics Group. His PhD thesis was entitled Angle-resolved studies of tin laser plasma extreme ultraviolet sources. Oran's research experience includes the study of the out-of-band, EUV and ion emission from tin laser produced plasmas and has published a number of peer reviewed papers on these topics.

Currently, his research at the LEC involves the development of a tin droplet laser plasma EUV source as well as the computational modeling of the source from the micron to meter scale.

S33

Modeling of "Mist Target" – the Ideal Target for LPP Source

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Generation efficiency of EUV radiation by laser-produced plasma (LPP) sources is defined by the effective coupling of the driver laser radiation with a target. Expected that usage of the distributed targets (DT) consisting of a number of small (from one to few micrometers) droplets distributed over the volume with a total size of a few hundred micrometers allows noticeably increase laser radiation absorption and in-band conversion efficiency. To simulate optical, atomic and hydrodynamic processes in LPP sources based on DT approach, an integrated model is being developed. The hydrodynamic plasma model includes diffusion-like radiation transport with 100 and more groups of spectral groups with well represented in-band EUV. Non-stationary ionization (recombination) processes are also included. Energy fluxes to and from a target surface are taken into account: electron and ion thermo-conductivity, radiative transfer in every spectral group, condensation and recombination of vapor and plasma. Verified atomic data are used for calculation opacity and emissivity. Results of a numerical simulation of are presented for various types of DT.

Presenting Author

S34

DPP with Liquid Tin Jet Electrodes: Status, Perspectives, Challenges

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RnD ISAN continues to work on new modification of DPP sources of EUV radiation based on liquid tin jet electrodes. First experiments with full cycle of liquid tin circulation are reported. Measurements of CE in short burst regimes demonstrate high CE (2.5%) and small source size. Expectation, nearest plans and challenges are being discussed.

Presenting Author

S35

Experimental and Theoretical Studies of Gd and Tb Radiation in 6.X Spectral Region

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Experimental studies of spectra of plasma of Gd and Tb in 6.X spectral region are reported. Spectra were excited in LPP and DPP types of radiation sources. Conversion efficiency of laser radiation (LPP) and stored electrical energy in 0.6% "in band" spectral interval have been measured. CE as high as 1.8% was demonstrated for special type of LPP target geometry. Experiments have been compared with predictions of detailed theoretical modeling.

Presenting Author

S36

Peculiarities of Modeling LPP Source at 6.X nm

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Some features of modeling LPP plasma source at 13.5 and 6.x spectral regions are analyzed by using the code RZLINE. The main attention is paid to the difference in emission spectra modeling at 13.5 nm and at 6.x nm. Some refinement of the method used for Sn should be done to calculate the spectra at 6.x. The detailed emission spectra of laser produced Gd and Tb plasmas are calculated for excitation by CO_2 laser with different pulse energies, pulse durations and power densities for different type targets. The conversion efficiency, anisotropy of radiation, size of source and other characteristics were obtained in a wide region of input parameters. The calculated data are compared with experiment.

Presenting Author

S37

Diagnostics Tools for EUV and BEUV Radiating Plasmas.

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In this paper we have presented a set of VUV – X-RAY diagnostic tools. It includes MCP based imaging systems with few nanoseconds time resolution for EUV (13.5 nm), BEUV (6.X nm) and X-Ray radiating plasmas plasma. Spectrographs covering a spectral region from 5 nm up to 60 nm provide simultaneously spectral, time and spatial resolution of studied plasmas. Technical characteristics, methods of applications and examples of usage are described.

Presenting Author

S38

Towards 20kW CO_2 Laser System for Sn-LPP EUV Source – Recent Developments

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Recent year has witnessed substantial development of high-power CO_2 laser system for LPP EUV source at Gigaphoton. This paper presents a summary of achievements to date on a path to 20 kW laser system for >500 W EUV power. The performance of a novel multi-line master oscillator is discussed in more detail for the first time. Experimental results show exceptionally high output stability in terms of pulse shape and energy complemented by electronically adjustable pulse shape and duration aimed to enable a study and optimization of CO_2-to-EUV conversion efficiency. Recent experimental results of efficient pre-amplification of the multi-line input by small and large-scale novel CO_2 amplifiers are discussed and shown to increase extraction efficiency and to deliver multi-kW output at high efficiency of over 60% from a compact package.

Presenting Author

S39

Multilayer Design for EUV lithography

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The research on developing Extreme Ultraviolet Lithography (EUVL) techniques is now exploring shorter wavelength range at 6.X nm after the great effort made at 13.5 nm. Multilayer structures (MLS) will be the base always for the reflective optics of the system, however new materials as well as new designs need to be explored. We are going to present recent results we have obtained in the development of new designs of MLS operating in these new challenging spectral regions. The designs are essentially derived with an optimization process based on an evolutive strategy. The algorithm has been already tested and proved at 13.5 nm showing significant improved performances compared with standard periodic designs. In fact, higher efficiency has been obtained with a-periodic designs. Furthermore these structures result less sensitive to thickness errors of the layers making less critical the ML growing process. Finally it has been proved that their performances are essentially not degraded by the harsh environmental effects which can heavily affect the surface of the capping layer.

Presenting Author

S40

Recent Progress of Beyond EUV (BEUV) Sources

Takeshi Higashiguchi[1,2], Takamitsu Otsuka[1], Noboru Yugami[1,2], Bowen Li[3], Deirdre Kilbane[3], Thomas Cummins[3], Colm O'Gorman[3], Padraig Dunne[3], Gerry O'Sullivan[3], Weihua Jiang[4], and Akira Endo[5]

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The UTA (unresolved transition array) emission responsible for the adoption of tin plasmas for 13.5 nm operation is scalable to shorter wavelengths, and Gd is shown to have a similar conversion efficiency to Sn at a higher plasma temperature, with a narrow spectrum centered at 6.7 nm [1,2]. We will show various properties of the 6.7-nm emission such as spectral behavior, conversion efficiency, and laser parameter dependences [3, 4].

[1] T. Otsuka *et al*., Appl. Phys. Lett. **97**, 111503 (2010); G. Tallents *et al*., Nat. Photonics **4**, 809 (2010).
[2] T. Otsuka *et al*., Appl. Phys. Lett. **97**, 231503 (2010).
[3] T. Otsuka *et al*. (submitted); T. Higashiguchi *et al*. (submitted).
[4] B. Li *et al*. (submitted).

Presenting Author

Takeshi Higashiguchi is an associate professor. He received his Ph.D. in engineering from Utsunomiya University. His research activities have focused on short-wavelength light sources, laser-plasma interaction, and plasma photonics devices.

S41

Extreme ultraviolet Source at 6.7 nm Based on a Low-density Plasma

Takamitsu Otsuka[1], Takeshi Higashiguchi[1,2], Noboru Yugami[1,2], Colm O'Gorman[3], Bowen Li[3], Thomas Cummins[3], Deirdre Kilbane[3], Padraig Dunne[3], Gerry O'Sullivan[3], Weihua Jiang[4], and Akira Endo[5]

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We demonstrate an efficient extreme ultraviolet (EUV) source for operation at 6.7 nm by optimizing the optical thickness of gadolinium (Gd) plasmas [1, 2]. Using low initial density Gd targets and dual laser pulse irradiation, we observed a maximum EUV conversion efficiency (CE) of 1.8%, which is 1.6 times larger than the 1.1% CE produced from a solid density target [3]. Enhancement of the EUV CE by use of a low-density plasma is attributed to the reduction of self-absorption effects. In addition, strong resonant line emission at 6.76 nm from a discharge-produced Gd plasma was also obtained [4].

[1] T. Otsuka *et al*., Appl. Phys. Lett. **97**, 111503 (2010); G. Tallents *et al*., Nat. Photonics **4**, 809 (2010).
[2] T. Otsuka *et al*., Appl. Phys. Lett. **97**, 231503 (2010).
[3] T. Otsuka *et al*. (submitted); T. Higashiguchi *et al*. (submitted).
[4] B. Li *et al*. (submitted).

Presenting Author

Takamitsu Otsuka is Ph.D. student. He received a MS from Utsunomiya University. His research activity has focused on shorter wavelength EUV source development.

S42

Radiance of Non-equilibrium Gd plasma

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Keldysh Institute of Applied Mathematics RAS, Moscow, Russia
NRC Kurchatov Institute, Moscow, Russia
Joint Institute of High Temperatures RAS, Moscow, Russia

Recent results on spectral measurements for Gd and Tb plasmas show the capabilities to use these elements for the next generation of EUV and soft X-ray radiation sources. The maximum emission points located on spectrum are around 6.8 nm for gadolinium and 6.5 nm for terbium. In 0.2 nm range the necessary emission may be obtained from Gd XVII – Gd XXI ions and Tb XVIII – Tb XXII ions. These highly charged ions have a high ionization potential and for equilibrium case the temperature of plasma needs to be heated to 100 eV and higher to produce the sufficient fraction of them.

Discharge and laser produced plasmas used in soft X-ray and EUV sources are in non-equilibrium state as a rule. This leads to the mismatch between of actual conditions of the plasma and its theoretical/computational estimations, because of different effects like non-Maxwellian electron distribution, self-absorption etc. leading to change ionic compound, state populations, emission intensity and spectrum.

In the report the emission properties of non-equilibrium Gd plasma is considered and the optimal emission conditions are explored. Kinetic parameters for non-equilibrium plasma including inelastic ion interactions with non-thermal electrons, emission and absorption data are obtained in the approach based on Hartree-Fock-Slater (HFS) quantum-statistical model and distorted waves approximation.

Presenting Author

S43

High Brightness EUV Light Source for Actinic Inspection & Microscopy

Peter Choi[1,2], Sergey V. Zakharov[1,2+], Raul Aliaga-Rossel[1], Aldrice Bakouboula[1], Otman Benali[1,2], Philippe Bove[1], Michèle Cau[1], Grainne Duffy[1], Osamu Iwase[1], Blair Lebert[2], Ouassima Sarroukh[2], Clement Zaepffel [2], Vasily S. Zakharov[2]

[1] NANO-UV sas, Villebon/Yvette, France
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Actinic mask defect inspection and metrology require high brightness EUV sources. The self-absorption of radiation limits the in-band EUV radiance of the source plasma and makes it difficult to attain the necessary brightness and power from a conventional single unit LPP and DPP EUV source. One possible solution is through multiplexing of multiple low etendue sources. NANO-UV is delivering a new generation of EUV light source, the CYCLOPS™, in which a micro-plasma pulsed capillary discharge is characterized by high brightness, low etendue and high irradiance at moderate output power without the use of external physical optics. Run-away electrons from hollow cathode in gas-filled capillary create a tight ionized channel and initiate a discharge. The very high discharge current density produces a hot micro-plasma intensively emitting the light in required EUV wavebands. Such a source could form the basic building block of EUV source through spatial-temporal multiplexing of several units to deliver the brightness and power required for actinic metrology. We report on the EUV source development including the extensive numerical modeling, which provided the basic parameters required for high irradiance operating regimes. A new Sn-alloy cathode material enhances the output. Based upon the multiplexing concept, a family of specially configured multiplexed source structures, the HYDRA™ design, is being introduced to address the mask metrology needs.

Presenting Author

Dr. Sergey V. Zakharov graduated from the Moscow Physical-Technical Institute. He received the doctor degree in physical-mathematical sciences from Kurchatov Institute of Atomic Energy, Moscow, Russia, in 1984. He joined Troitsk Institute of Innovation and Fusion Research (TRINITI), Russia, in 1981, where he is currently Head of the theoretical laboratory. His works concern plasma turbulence theory, nonlinear waves, charged particle beams, radiation-magnetohydrodynamics and non-equilibrium plasma theory in HEDP and ICF. For works on interaction of high power electron beams with dense gas he was rewarded the State Prize for young scientists and engineers in 1987. For researches on high energy density physics and radiating multicharged ion plasma he was rewarded the Great Government Reward in 1997. Since 1999 he joined EPPRA SAS, France, as a Principal Scientist. He works on the theory of non-equilibrium heavy-ion plasmas and modeling of discharge and laser produced plasma radiation sources. Under his leadership the radiation-magnetohydrodynamic codes ZETA and Z* were created and are being developed.

S44

Properties of High Intensity Radiation Plasma Sources

S. V. Zakharov[abe+], V.S. Zakharov[∝], P. Choi[ab], G. O'Sullivan[d], A.V. Berezin[c], A.S. Vorontsov[c], M.B. Markov[c], S.V. Parotkin[c], A. Y. Krukovskiy[c], V. G. Novikov[c]

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The high intensity radiation in plasma light sources is produced by multicharged ion non-equilibrium plasma. Understanding of complex plasma dynamics and radiation processes is a key issue in power and brightness optimization in radiation plasma sources. The innovative hybrid 2-3D computational code based on the Z* code and its commercially available version Z*BME are designed under international collaborative project FIRE in the framework of FP7 IAPP to model multicharged ion plasmas in experimental and industrial facilities using a hybrid (particle-in-cell + magnetohydrodynamics + non-equilibrium ionization kinetics + multigroup spectral ray-tracing) approach including fast particles and plasma 3D dynamics in an electromagnetic field, the advanced atomic physics models and the spectral radiation transport. The multiphysics code is used to model laser-produced plasma and discharge-produced plasma to understand current physical processes and to optimize on that base the sources by brightness and delivered power for EUV lithographic and metrology applications. The radiation plasma dynamics, the spectral effects of self-absorption in laser-produced plasma and discharge-produced plasma are considered. The radiance and conversion efficiency of laser energy to EUV radiation in LPP is discussed. The generation of fast electrons and an enhancement of the radiance of a fast micro-plasma pulsed discharge created in a capillary wall confined structure is optimized.

Presenting Author

S45

EUV Lithography Light Source Power Scaling in Practice - LDP Source Development at XTREME Technologies

Harald Verbraak

XTREME technologies, Aachen, Germany

For extreme ultraviolet lithography (EUVL) to transition to high volume manufacturing (HVM), a powerful EUV light source emitting a radiation in a 2 % bandwidth centered on 13.5 nm will soon be needed. To meet the challenge, over the past 10 years, XTREME Technologies has been developing an LDP (laser assisted discharge plasma) light source where plasma is generated between two rotating discs. Partially immersed in baths filled with liquid Tin, the discs are wetted and covered with a thin layer of liquid Tin. A pulsed laser beam focused on one of the discs evaporates a small amount of Tin and generates a Tin cloud between the two discs. Next a capacitor bank, which is connected to the discs via the liquid Tin, discharges and converts the Tin cloud into plasma that heats up to an electronic temperature of 20 eV. Pinched by the high current, the plasma emits the EUV radiation. This process is repeated several thousand times per second. The EUV-power that reaches the intermediate focus aperture (IF) – the interface between the source and the scanner – depends primarily on input electrical power, collectable EUV optical power and the transmission through the EUV collecting mirrors.

In this presentation, an overview of the requirements and the current status of the source development will be presented. Particularly, the feasibility of 50 kW electrical power source head enabling 48 W EUV optical power will be detailed.

Presenting Author

Harald Verbraak obtained his PhD in 2008 at the Physical Chemistry group at Laser Centre at the Vrije Universiteit in Amsterdam in the field of spectroscopy of ionic complexes. Since June 2008 he is working as a research engineer for Philips EUV/Xtreme technologies (since 2010) in Aachen. He is involved in source efficiency and debris mitigation projects.

S46

High Brightness Electrodeless Z-Pinch™ EUV Source for Mask Inspection Tools

Deborah Gustafson, Stephen F. Horne, Matthew M. Besen, Donald K. Smith, Matthew J. Partlow, Paul A. Blackborow

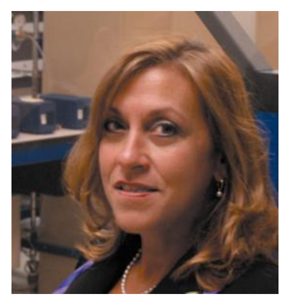
Energetiq Technology, Inc., Woburn, MA, USA

Energetiq's EQ-10HB has been selected as the source for pre-production actinic mask inspection tools. This improved source enables the mask inspection tool suppliers to build prototype tools with capabilities of defect detection and review down to 16nm design rules. In order for the production mask inspection tools to be cost effective, however, much brighter source will be required by 2013-2015.

In this presentation we will present new source technology being developed at Energetiq to address the critical source brightness issue. The new technology will be shown to be capable of delivering brightness levels sufficient to meet the HVM requirements of AIMS and ABI and potentially API tools. The high brightness EUV plasma is modeled to have a brightness of up to 100W/mm^2-sr. We will explain the source design concepts, discuss the expected performance and present the modeling results for the new design.

Presenting Author

Debbie Gustafson is an industry veteran for over 20 years and has held various management positions in technical Sales and Marketing in the Semiconductor Equipment Industry. Her focus has been on component and subsystem equipment and service. Ms. Gustafson's is a senior manager at Energetiq Technology, Inc. in Woburn, Massachusetts as their Vice President of Marketing and Sales. Her responsibility also includes marketing and the management of manufacturing and finance. She has successfully driven the company to become the leading supplier of EUV sources globally. Ms. Gustafson has vast knowledge in the international markets with a focus on Asia. She has managed the opening of a subsidiary in Japan and a joint venture sales and service organization in Korea. She also has extensive experience in negotiating multimillion dollar contracts and supplier agreements.



Currently Ms. Gustafson is the past chairperson of the SEMI New England Committee. She holds a BS in Mechanical Engineering and an MBA in Management from Bentley College.

S47

Soft X-ray Source Development at Energetiq Technology

Deborah Gustafson, Stephen F. Horne, Matthew M. Besen, Donald K. Smith, Matthew J. Partlow, Paul A. Blackborow

Energetiq Technology, Inc. Woburn, MA, USA

The commercially successful EQ-10 EUV source platform can also be used to generate soft x-ray photons at 430eV by using Nitrogen as a source gas (400mW/2 pi, 2.88nm, Nitrogen). The source is used as an illumination system for water window x-ray microscopy. Published data will be shared by integrating the Energetiq EQ-10 with an Xradia soft x-ray microscope. Recent work has been performed to improve the image time and source running time. This data will be shared.

Presenting Author

S48

Investigating the effects of laser power density and pulse duration on the 6.7-nm BEUV emission

Thomas Cummins[a)], Takamitsu Otsuka[b)], Colm O'Gorman[a)], Padraig Dunne[a)], Gerry O'Sullivan[a)] Noboru Yugami[b)] and Takeshi Higashiguchi[b)]

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b) Utsunomiya University, Tochigi, Japan

The research field of Extreme Ultraviolet (EUV) source development has identified Beyond Extreme Ultraviolet (BEUV) radiation sources as the next step in the lithography process after the implementation of 13.5 nm. Radiation at 6.X nm has been investigated as such a source, due to improved reflectivity from lanthanum boron carbide (La/B_4C) mirrors, currently 49.83% at 6.656 nm [1]. Some recent theoretical modeling [2] has predicted that a plasma temperature of around 110 eV will be required to produce the ionization stages necessary for the emission of an unresolved transition array (UTA) around 6.5 - 6.7 nm in the spectrum of Gadolinium (Gd). Experiments are being carried out on Gd laser produced plasmas with variation of laser parameters to observe the UTA emission and the maximum BEUV conversion efficiency (CE).

In this work we will present results on the influence of laser pulse duration and irradiating laser power density on the conversion efficiency (CE). Power density scans, such as those previously reported [3, 4], were carried out. Three lasers with nanosecond, picosecond and femtosecond pulse durations were employed to irradiate planar Gd targets. A power density range of 10^{11} - 10^{15} W/cm^2 was covered by varying the pulse energies of these lasers. The effects of increasing power density on CE will also be presented.

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Presenting Author

Thomas Cummins is a 3rd year PhD student. He graduated with a B.Sc. in Applied Physics from Dublin City University in 2009 and joined the Spectroscopy group of University College Dublin in September 2009 as a PhD student. His research interests include laser produced plasma for development of Extreme Ultraviolet light sources, laser Sn plasma interaction and shorter wavelength BEUV sources. His project supervisor is Prof. Padraig Dunne.

S49

The Effect of Viewing Angle on EUV Spectra of Laser Produced Gadolinium Plasmas

Colm O'Gorman[1], Takamitsu Otsuka[2], Bowen Li[1], Deirdre Kilbane[1], Thomas Cummins[1], Padraig Dunne[1], Emma Sokell[1], Gerry O'Sullivan[1], Akira Endo[4], Noboru Yugami[2,3], and Takeshi Higashiguchi[2,3]

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[4]*Waseda University, Research Institute for Science and Engineering, Waseda University, Shinjuku, Tokyo, Japan*

We demonstrate the effect of viewing angle on the EUV emission spectra of the Gadolinium unresolved transition array centered at 6.7 nm. The experiment is carried out using a variety of power densities, using two laser pulse durations: 10 ns and 150 ps and two target densities: 100% and 30%. The detected spectra are shown to have a strong dependence on viewing angle when produced with the 10 ns pulse duration attributed to absorption by low ion stages of Gd [1]. This is in agreement with previously detected emission spectroscopy of Sn laser produced plasmas centered at 13.5 nm [2]. This absorption is less pronounced when using the 150 ps laser due to plasma expansion effects. Measurement of conversion efficiency as a function of angle is also carried out using a calibrated diode coupled with a Mo/B_4C multilayer mirror.

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[2] P. Hayden *et al.*, Microelectron. Eng. **83**, 669 (2006).

Presenting Author

Colm O' Gorman is a PhD student with the Atomic, Molecular and Plasma Physics group in UCD. He received his B.Sc in Physics from University College Dublin in 2009. His research activities have focused on EUV emission spectroscopy and ion spectroscopy of laser produced plasmas.

S50

Development of Novel EUV Source Collector Module Using a Tin Based Liquid Metal Alloy

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[2] *UCD School of Physics, UCD, Stillorgan Rd, Dublin 4, Ireland*
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[4] *Institut polytechnique de Grenoble, Grenoble, France*

Recent progress on the development of a source collector module for use in EUV metrology at 13.5 nm in the semiconductor processing industry is presented. The module is based around the use of a novel liquid metal, grazing-incidence collector mirror. The nature of the collector allows it to be in close proximity to an LPP source, where the source uses the same liquid metal as the plasma fuel. The collector can then absorb the debris and fast ions from the source as it has a self-healing surface. Thus the collector maintains a constant throughput of photons at intermediate focus.

Here we present the development of a stand-alone unit for prototype demonstration utilizing a 4 KHz, 100 W Nd: YAG laser, supplied by Edgewave.

Presenting Author

Paul Sheridan is a founding member of NewLambda Technologies. He received his Ph.D. in 2008 from UCD Dublin for work on double photo-electron spectroscopy. Since then he has worked on the development of EUV sources and collector optics. Previously he received his MSc in the development of novel targets for laser produced plasma EUV sources. He has over 10 years design experience of vacuum systems and vacuum automation.

S51

High Brightness Source Collector Module for EUV Metrology

Kenneth Fahy[1], Paul Sheridan[1], Padraig Dunne[2], Enda Scally[2], Niall Mulligan[3], Emilien Foiret[4] and Fergal O'Reilly[2]

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[4] Institut polytechnique de Grenoble, Grenoble, France

NewLambda Technologies (www.NewLambda.com) are developing a high brightness source collector module for metrology applications. The collector optic is a liquid metal coated ellipsoid section. The optic rotates slowly to maintain a uniform and stable thickness of liquid metal over the interior surface. The source is a laser produced plasma which uses the same liquid metal as the plasma fuel. This allows close proximity of the collector to the source without need for debris mitigation before the collector. Thus the module is being designed to deliver a clean, debris-free, high brightness source of 13.5 nm photons to match industry demands. We report on recent progress on EUV characterization and we present our development plans for 2012.

Presenting Author

Kenneth Fahy is CEO and co-founder of NewLambda Technologies. He received his Ph.D. from UCD Dublin in 2007 for work at NIST Maryland and UCD. Since then has worked on liquid metal mirror development and established the mirror fabrication process, part of NLT's IP portfolio. Prior to his PhD, Kenneth worked as a product development engineer for CorkOpt Ltd, an Irish start-up photonics company who were subsequently acquired by StorkerYale Inc.

S52

Radiation Sources in the Extreme Ultraviolet and Soft X-ray Region

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Possible extreme ultraviolet (EUV) and soft x-ray (SXR) sources have been identified using the FAC relativistic code. Theoretical emission spectra resulting from the 4d-4f and 4p-4d transitions in Pd-like to Rb-like ions of lanthanum through actinium are presented. Characterization of these sources is achieved by applying the unresolved transition array (UTA) model. The resulting mean wavelengths and spectral widths are also shown. In future the laser produced plasma (LPP) technique may be used to generate these radiation sources for applications in exciting fields such as microscopy, spectroscopy and lithography.

Presenting Author

S53

Investigation of Spatial and Spectral Characteristics of EUV Emission from Laser Assisted Vacuum Arc

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In this contribution the investigation of extreme ultraviolet (EUV) emission from Laser Assisted Vacuum Arc (LAVA-lamp) discharge is presented. In this system the high-current discharge between two rotating electrodes covered with a thin liquid tin film is triggered by local laser ablation of electrode material. The plasma is studied by means of the following techniques:

- absolutely calibrated time integrated EUV spectroscopy
- 2 μm spatially resolved time integrated in-band EUV imaging of plasma pinch region
- temporal characterization of in-band EUV emission with a filtered fast photodiode
- time- and spatially-resolved fast gated visible emission spectroscopy
- time of flight diagnostic of ions with a Faraday cup
- Characterisation of plasma constituent material by deposition analysis.

The results of this investigation will enable better understanding of the physical properties of these kinds of discharge plasmas, such as electron densities, temperatures and characteristic dimensions along with ion species and angular debris characteristics. The obtained knowledge can be used for further optimisation of e.g. conversion efficiency, source brightness, or total in-band EUV output.

Presenting Author

S54

Light for the Nano-world

Larissa Juschkin[1,2], Serhiy Danylyuk[2], Matus Banyay[2], Sascha Brose[2], Stefan Herbert[2], Aleksey Maryasov[2], Ralf Freiberger[2], Johannes Hauck[2], Peter Loosen[2]

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The spectral range of extreme ultraviolet (XUV, 1 - 50 nm or EUV, around 13.5 nm) radiation combines the advantages of short wavelength and efficient light-matter interaction enabling lateral- and depth-resolutions in the nanometer range. The interaction cross sections maximize in this spectral range and are dominated by absorption and elastic scattering which assures an efficient use of photons and high surface-, thin-film- and structure-sensitivity. Compared to other spectral ranges, EUV radiation has a typical penetration depth into solid material of only ~ 10 – 100 nm which allows investigations on a nanometer scale to be performed also into third dimension. Furthermore, these wavelengths are well matched to the primary atomic resonances of most elements, making possible many element- and chemically- specific spectroscopies and spectro-microscopies.

The burgeoning research area, using XUV radiation, incorporates many scientific fields such as microscopy, defect inspection, reflectometry, scatterometry, photoemission spectroscopy and microscopy, lithography, damage studies and photo etching. The talk addresses the challenges and achievements of XUV light generation in hot plasmas and its application in metrology and structuring.

Presenting Author

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Non-LTE Plasma Modeling with Cretin

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Cretin is a multi-dimensional non-LTE radiation transport code used to model plasmas for a wide range of applications [1]. It has been used extensively in the fields of inertial confinement fusion, magnetic fusion, and laser-produced plasmas. The core capability of the code is the self-consistent simulation of atomic kinetics and radiation transport in 1- to 3-dimensional geometries, including optically thick lines with detailed line shapes. Other physical processes include laser absorption, conduction, and (in 1-D) Lagrangian MHD. All physical processes are driven by data derived from atomic kinetics calculations. Cretin can use atomic data from a variety of sources. It can also generate atomic models for any element, using a screened-hydrogenic superconfiguration approach [2]. These models are sufficiently accurate for many simulations that do not require spectroscopic accuracy, while remaining computationally inexpensive enough for use within a radiation-hydrodynamics code.

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

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Multilayers for present and future generations of EUVL

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The wavelength choice of 13.5nm for the first generation of EUVL was dictated by the existence of high reflectivity multilayer coatings at this wavelength. Champion reflectivity of 70.15% for these multilayers has been reported [1]. Actual optics demonstrate reflectivity in the range of 68% to 69.5%. These values of reflectivity are relatively close to the maximum theoretically calculated reflectivity of 75% for ideal Mo/Si structures. The difference between theoretical and experimental reflectivity for the most promising multilayers targeting the 2nd generation EUVL wavelength 6.7nm is much larger. Calculated reflectivity at this wavelength can be as high as 67% to 80% depending on which optical constants are used for the calculations [2, 3]. Today, the highest reported reflectivity at 6.7nm is ~50% [4], which is far below 60-65% required for a multiple mirror optical system. A more dramatic shortcoming between theory and experiment is observed at shorter wavelengths, such as ~4.4nm, ~3.2nm, etc., which can be considered as candidates for future generations of EUVL. This paper presents a current status of the multilayer structures development at RIT for the present and future generations of EUVL.

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Yuriy Platonov received MS degree in physics in 1977 from Moscow State University and PhD degree from Nizhny Novgorod State University in 1989. From 1978 to 1991 he worked at the Institute of Applied Physics of Russian Academy of Sciences (RAS) and his activities were focused on laser produced plasma diagnostics, pulsed laser deposition technology and multilayer X-ray optics. From 1991 to 1995 he ran the X-ray Optics Laboratory at the Institute for Physics of Microstructures of RAS. Since 1995 he is Director, Coatings and Senior Science Adviser at Rigaku Innovative Technologies, formerly Osmic. His field of scientific interests includes physics of artificial thin film structures, design and deposition of x-ray multilayer optical elements, X-ray analytical instrumentation, and multilayer neutron optics.

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EUV Microscopy - a User's Perspective

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The saddest limitation of light microscopy including all its expensive gadgets like the confocal, Multi-photon, Total Internal Reflection etc. is the diffractional (Abbe's) limitation of resolution. The practical border of the XY-resolution is about 200 nm for visible light and the best lens. This limitation impedes the structural investigations in cell biology because the common cell size ranges between 10-20 um, which corresponds to only 50-100 lines of resolved details along the cell. Thus, in the best case scenario, we can resolve ca. 2,000-8,000 details only (assuming the cell is a perfect circle). In case of a 2um large platelet this would shrink to ca. 78 details and for the 1um bacteria only 20. Usually we do not achieve even these numbers, especially if the Nyquist criteria for sampling have been not matched. Surely, there are plenty tools which allow going beyond the Abbe's limit but each one brings other limitations with it (Table below).

	Practically achievable XY resolution, nm	Features, Limitations
Fluorescence microscopy, including confocal and multi-photon	200 nm	- simple, suitable for live cells - multiple labeling, large field of view - suitable for fast acquisition (30 fps and more) - low resolution
Electron microscopy	1 nm (bio-EM) 10 nm (immuno-EM)	- vacuum: unsuitable for most live cell studies - thin samples only (70-300nm): reduced information - expensive sample preparation - immunolabeling difficult and decreases the resolution
Super-resolution fluorescence: STORM, PALM, STED	40 nm	- slow: unsuitable for many live cell studies - require photo switchable fluorescent dyes or proteins
Near UV microscopy	100 nm	- requires special expensive lenses - poor signal/noise ratio - only 2-fold gain of resolution
EUV microscopy now	40 nm	- requires special light sources and X-ray optics - narrow field of view

Improving the resolution to 40 nm increases the amount of detectable details 25-fold, down to 25 nm 64-fold. 25 nm is the diameter of a ribosome or a microtubule. All membrane organelles are larger than this. On the other hand, cells possess natural diversity. Studying just a few cells usually not enough; we need statistics. Therefore, we biologists are so desperate looking for *simple* tools which would allow us imaging both *live* and fixed cells with less than 25nm resolution without compromising the *field of view*.

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Time Resolved EUV Spectra of Laser Produced Tin Plasmas

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Extensive modeling predicts that laser produced tin plasmas, with electron temperatures of 30 to 70 eV can emit brightly in the desired bandwidth for Extreme Ultraviolet Lithography (EUVL) [1, 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]. In order to assist the ongoing modeling of laser produced plasmas (LPPs) we will present time resolved spectra of tin plasma UTA in the 9–18 nm region. The plasmas were produced by focusing 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 ($\Delta\lambda$ ~ 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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Dr. Paddy Hayden is a SFI funded Postdoctoral Research Fellow in the National Centre for Plasma Science and Technology at Dublin City University. He received his PhD from University College Dublin in 2007 studying atomic and plasma physics processes in plasma based extreme ultraviolet light sources. He was awarded an Irish Research Council for Science, Engineering and Technology postdoctoral research fellowship immediately after receiving his doctorate degree and joined with Professor J. T. Costello's group at DCU. Dr. Hayden also collaborated with many university-based researchers, small enterprises and multinational companies throughout Europe, Asia and the United States. He has co-authored more than 30 scientific journal articles, book chapters, industrial technology transfer reports and patents in the fields of laser-produced plasma applications, LIBS, plasma diagnostics, plasma-facing components and the interaction of intense Free Electron Laser extreme ultraviolet light with matter. While maintaining his broader research interests, his main focus is currently on the design and implementation of novel extreme ultraviolet light sources as part of a SFI Ireland Investigator Grant (No. 02/IN.1/I99), a collaboration between UCD, DCU and TCD.

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