2013 International Workshop on EUV and Soft X-Ray Sources

November 3-7, 2013
Dublin ▪ Ireland

Workshop Abstracts

EUV Litho, Inc.

2013 International Workshop on EUV and Soft X-ray Sources is organized by:

Please visit www.euvlitho.com for additional information.

2013 International Workshop on EUV and Soft X-ray Sources

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Welcome

Dear Colleagues;

We are ready to welcome you to the 2013 International Workshop on EUV and Soft X-Ray Sources in Dublin, Ireland.

4th annual source workshop is now the largest annual gathering of EUV and XUV source experts. 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 and will be made available at no cost to all.

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

Best Regards

Vivek Bakshi
Organizing Chair, 2013 International Workshop on EUV and Soft X-Ray Sources

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 (ALSphotonics)
Akira Endo (HiLase)
Henryk Fiedorowicz (Military University of Technology, Poland)
Torsten Feigl (OptiXfab)
Francesco Flora (ENEA)
Debbie Gustafson (Energetiq)
Ahmed Hassanein (Purdue)
Takeshi Higashiguchi (Utsunomia University)
Larissa Juschkin (Aachen University)
Hiroo Kinoshita (Hyogo University)
Oleg Kritsun (GlobalFoundries)
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)
Shunko Magoshi (EIDEC)
Hakaru Mizoguchi (Gigaphoton)
Ulrich Mueller (Carl Zeiss)
Katsuhiko Murakami (Nikon)
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 (Universiy 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)
Mikhail Yurkov (DESY)
Sergey Zakharov (EPPRA)
Vivek Bakshi (EUV Litho, Inc.) - Organizing Chair
Padraig Dunne (UCD) - Organizing Co-Chair

Workshop Agenda

2013 International Workshop on EUV and Soft X-Ray Sources

Agenda Outline

Short Courses

Location: *TBA* Lecture Hall, UCD Campus

Sunday November 3 - November 4, 2013

Sunday, November 3, 2013, 8:30 AM- 4:30 PM
Fundamental Principals of Optical Lithography
Instructor: Dr. Chris Mack

Monday, November 4, 8:30 AM -12:30 PM
Introduction to EUV Lithography
Instructor: Dr. Vivek Bakshi

Separate Registration Required for Short Course. Please visit www.euvlitho.com for course information and registration.

Monday, November 4, 2013

Location: Newman House, Stephen’s Green, Dublin

6:00 - 7:00 PM	Reception and Speaker Prep

Tuesday, November 5, 2013

Location: George Moore Auditorium, UCD Campus, Dublin

7:45 AM	Pickup at the Hotel (Stephen’s Green and Burlington Hotel)
8:30 AM – 11:30 AM	Workshop Presentations
12:05 AM - 1:20 PM	Lunch
1:20 PM – 5:30 PM	Workshop Presentations
5:30 PM – 6:30 PM	Poster Session and Reception
6:30 PM	Depart for Off-Site Dinner (Pickup at Auditorium)

Wednesday, November 6, 2013

Location: George Moore Auditorium, UCD Campus, Dublin

7:45 AM	Pickup at the Hotel (Stephen's Green and Burlington)
8:30 AM – 1:15 PM	Workshop Presentations
1:15 PM	Depart for off-site Lunch and tour
	Tour: Battle of the Boyne (http://www.battleoftheboyne.ie/) (Pickup at the Auditorium)

Thursday, November 7, 2013

Location: Newman House, Stephen's Green, Dublin

Technical Working Group (TWG) Meeting

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

WORKSHOP AGENDA

2013 International Workshop on EUV and Soft X-Ray Sources

November 3-7, 2013, Dublin, Ireland

Monday, November 4, 2013 (Newman House)

6:00 PM – 7:00 PM Reception and Registration

Tuesday, November 5, 2013 (George Moore Auditorium)

8:30 AM Session 1: Welcome and Announcements

Introduction and Announcements (Intro-1)

Joe Carthy, UCD

Vivek Bakshi, EUV Litho, Inc., USA

8:40 AM Session 2: Keynote Session -1

Session Chair: Katsuhiko Murakami (Nikon)
EUV Lithography: Current and Future Requirements and Options? (S2)
Vadim Banine
ASML, Netherlands

Enabling EUVL for HVM Insertion (S3)
Mark Phillips
Intel Corporation

Awards and Announcements – Padraig Dunne (UCD)

Break 10:10 AM

10:25 AM Session 3: HVM EUV Sources

Session Co-Chairs: Vadim Banine (ASML) and Hakaru Mizoguchi (Gigaphoton)

Update of High CE, High Power HVM LPP-EUV Source Development (S21) (Invited)

Hakaru Mizoguchi[1], Hiroaki Nakarai[2], Tamotsu Abe[2], Takeshi Ohta[2], Krzysztof M Nowak[2], Yasufumi Kawasuji[2], Hiroshi Tanaka[2], Yukio Watanabe[2], Tsukasa Hori[2], Takeshi Kodama[2], Yutaka Shiraishi[2], Tatsuya Yanagida[2], Tsuyoshi Yamada[2], Taku Yamazaki[2], Shinji Okazaki[1] and Takashi Saitou[2]

[1]Gigaphoton Inc. Oyama facility, JAPAN

[2]Gigaphoton Inc. Hiratsuka facility, JAPAN

BEUV Nanolithography: 6.7 or 11 nm? (S19) (Invited)

N. I. Chkhalo and N. N. Salashchenko

Institute for physics of microstructures of RAS, Nizhny Novgorod, Russia

Development of High Brightness and High Average Power Picosecond Thin Disc Laser for Short Wavelength Light Sources in HiLASE Project (S24)

Taisuke Miura[1], Michal Chyla[1,2], Martin Smrž[1], Siva Sankar Nagisetty[1,2], Patricie Severová[1,2], Ondřej Novák[1], Pawel Sikocinski[1,2], Akira Endo[1], and Tomáš Mocek[1]

[1]HiLASE Project, Institute of Physics AS, CR, Na Slovance 2, 182 21 Prague 8, Czech Republic

[2]Czech Technical University in Prague, Břehová 7, 115 19, Prague, Czech Republic

Research Review on Plasma-based EUV Sources at RnD-ISAN/EUV Labs (S40)

V. M. Krivtsun[1, 2], R.R. Gayasov[1, 2], O. F. Yakushev[1], D. B. Abramenko[1], A. Yu. Vinokhodov[1] and K. K. Koshelev[1, 2]

[1] RnD-ISAN /EUV Labs, Moscow, Troitsk, Russia

[2] Institute for Spectroscopy RAS, Moscow, Troitsk, Russia

A Systematic Study of Colliding Plasmas for EUVL (S25)

Emma Sokell, Colm O'Gorman, Bowen Li, Thomas Cummins, Padraig Dunne, Fergal O'Reilly, Paddy Hayden, and Gerry O'Sullivan

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

Lunch 12:05 PM

1:20 PM Session 4: Modeling

Session Co-Chairs: Padraig Dunne (UCD) and Chihiro Suzuki (NIFS, Japan)

Development of Radiation Hydrodynamic code STAR for EUV Plasmas (S15)

Atsushi Sunahara[1], Katsunobu Nishihara[2], Akira Sasaki[3], Nozomi Tanaka[2], Shinsuke Fujioka[2], and Hiroaki Nishimura[2]
[1] Institute for Laser Technology, Japan
[2] Institute of Laser Engineering, Osaka University, Japan
[3] Kansai Photon Science Institute, Japan Atomic Energy Agency, Japan

Modeling of the Laser Plasma Interaction for the Development of Efficient EUV Sources (S17)

Akira Sasaki
Quantum Beam Science Directorate, Japan Atomic Energy Agency, Kyoto, Japan

Observations of EUV Spectra from Highly Charged Heavy Ions in Optically Thin Plasmas for Benchmarking of Models (S16)

Chihiro Suzuki[1], Fumihiro Koike[2], Izumi Murakami[1], Naoki Tamura[1], Shigeru Sudo[1], Takeshi Higashiguchi[3], Gerry O'Sullivan[4]
[1] National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
[2] Sophia University, 7-1 Kioi-cho, Chiyoda-ku, Tokyo 102-8554, Japan
[3] Utsunomiya University, 7-1-2 Yoto, Utsunomiya 321-8585, Japan
[4] University College Dublin, Belfield, Dublin 4, Ireland

Fundamental Atomic Process in Source Development for Beyond EUV Lithography and "Water Window" Imaging (S38)

Bowen Li[1], Takeshi Higashiguchi[2], Takamitsu Otsuka[1], Weihua Jiang[3], Akira Endo[4], Emma Sokell[1], Padraig Dunne[1], and Gerry O'Sullivan[1]
[1] School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
[2] Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), and Optical Technology Innovation Center (OpTIC), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan
[3] Department of Electrical Engineering, Nagaoka University of Technology, Kami-tomiokamachi 1603-1, Nagaoka, Niigata 940-2188 Japan
[4] HiLASE Project, Institute of Physics AS, CR, Prague 8, Czech Republic

Advances in Modeling of Physical Processes in Plasma-based Sources of EUV Radiation (S39)

V.V. Ivanov[1, 2], V. G. Novikov[1, 3], A.S. Grushin[1, 3], I. Yu. Vichev[1, 3], D.A. Kim[1, 3], V. Konovalov[1, 3], A.D. Solomyannaya[1, 3], K.K. Koshelev[1, 2], V. M. Krivtsun[1, 2], A.M. Yakunin[4], A. Bratchenia[4], V.Y. Banine[4]
[1] RnD-ISAN, Troitsk, 142190 Russia
[2] Institute for Spectroscopy RAS, Troitsk, 142190 Russia
[3] Keldysh Institute of Applied Mathematics RAS, Moscow, 125047 Russia
[4] ASML, Veldhoven, The Netherlands

Pulsed-power Based Bright EUV Light Source for Metrology (S48)

S. Zakharov
NAEXTSTREAM, France

Break 3:20 PM (15 Minutes)

3:35 PM Session 5: Optics

Session Co-Chairs: Yuriy Platonov (RIT) and Torsten Feigl (optiXfab)

Collector Development with IR Suppression and EUVL Optics Refurbishment at RIT (S30) (Invited)

Yuriy Platonov[1], Michael Kriese[1], Raymond Crucet[1], Yang Li[1], Vladimir Martynov[1], Licai Jiang[1], Jim Rodriguez[1], Ulrich Mueller[2], Jay Daniel[2], Shayna Khatri[2], Adam Magruder[2], S. Grantham[3], C. Tarrio[3], T. B. Lucatorto[3]
[1]Rigaku Innovative Technologies, Auburn Hills, MI, USA
[2]Integrated Optical Systems – Tinsley, Richmond, CA, USA
[3]National Institute of Standards and Technology, Gaithersburg, MD, USA

EUV Optical Elements with Enhanced Spectral Selectivity for IR Radiation (S31)

V. V. Medvedev[1], A. E. Yakshin[1], R. W. E. van de Kruijs[1], V. M. Krivtsun[2], E. Louis[1,3] and F. Bijkerk[1,3]
[1]FOM Institute DIFFER, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands
[2]Institute for Spectroscopy RAS, Fizicheskaya Str., 5, Troitsk, Moscow Region, 142190 Russia
[3]MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

Design of Freestanding Film Elements for HVM tools of EUV Nanolithography (S28) (Invited)

Alexey Yakovlevich Lopatin, Nikolay Nikolaevich Salashchenko
Institute for Physics of Microstructures, Nizhny Novgorod, Russia

Characterization of Metrology Tools and Optical Components for HVM EUV Sources (S35) (Invited)

F. Scholze[a], C. Laubis[a], A. Gottwald[a], and T. Feigl[b]
[a]Physikalisch-Technische Bundesanstalt, Abbestr. 2-12, 10587 Berlin, Germany
[b]optiX fab GmbH, Hans-Knöll-Str.6, 07745 Jena, Germany

LPP Collector Mirrors – Coating, Metrology and Refurbishment (S34) (Invited)

Torsten Feigl[a], Marco Perske[a], Hagen Pauer[a], Tobias Fiedler[a],
Christian Laubis[b], Frank Scholze[b]
[a]optiX fab GmbH, Hans-Knöll-Str.6, 07745 Jena, Germany
[b]Physikalisch-Technische Bundesanstalt, Abbestr. 2-12, 10587 Berlin, Germany

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

7:00 PM Depart for Off-site Dinner (Marion Hotel)

End of Day 2

5:30 PM Session 7: Poster Session

Session Chair: Greg Denbeaux (University of Albany)

Topic: HVM Sources

Energy Fraction of CO_2 Laser Absorbed in EUV Source Plasma (S14)
Shinsuke Fujioka[1], Teruyuki Ugomori[1], Kensuke Yoshida[1], Chaogang Li[1], Atsushi Sunahara[2], Katsunobu Nishihara[1], Nozomi Tanaka[1], and Hiroaki Nishimura[1]
[1] Institute of Laser Engineering, Osaka University, Japan
[2] Institute for Laser Technology, Japan

Radiation of Gd and Tb Plasmas in 6.X nm Spectral Region (S46)
V. Krivtsun, O. Yakushev, R. Gayazov, D. Abramenko and K. Koshelev
RnD-ISAN / EUV Labs, Troitsk, Moscow

Topic: EUV Sources for Mask Metrology

Microwave EUV Light Sources for Photolithography (S13)
Sho Oe[1], Saya Tashima[1], Masami Ohnishi[1], Waheed Hugrass[2] and Hodaka Osawa[1]
[1]Kansai university, Faculty of Engineering Science, Department of Electrical and Electronic Engineering, 3-3-35 Yamate-cho, Suita-shi, Osaka 564-8680, Japan
[2]University of Tasmania, School of Computing and Information Systems, Private Bag, 1359, Newnham, Tasmania 7250, Australia

The Energetiq EQ-10 EUV Source for metrology - Review of Recent Data (S29)
Stephen F. Horne, Matthew J. Partlow, Deborah S. Gustafson, Matthew M. Besen, Donald K. Smith, Paul A. Blackborow
Energetiq Technology Inc., Woburn, MA, USA

Effect of Misalignment in Laser-droplet Interaction on the Three Dimensional EUV Emission and Ion Distribution (S37)
Andrea Giovannini and Reza S. Abhari
Laboratory for Energy Conversion, Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland

2D-Gas Dynamics Transient Modeling of Hot Gas Bubble Formation EUV Source Chamber (S43)
V. Konovalov[1,3], V.G. Novikov[1,3], V.V. Ivanov[2,3], K. N. Koshelev[2,3], A.M. Yakunin[4], V. Y. Banine[4]
[1] Keldysh Institute of Applied Mathematics, Moscow, Russia
[2] Institute for Spectroscopy RAS, Troitsk, Russia

[3]*RnD-ISAN/RnD-M, Troitsk, 142190 Russia*
[4]*ASML, Veldhoven, Netherlands*

Transmission Grating Spectrometer for EUV Source Characterization from the UV to the EUV (S47)

H.M.J. Bastiaens[1], C. Bruineman[2], B. Vratzov[1,3], and F. Bijkerk[1,4]
[1] *MESA+ Institute for Nanotechnology, University of Twente, The Netherlands*
[2] *Scientec Engineering, The Netherlands*
[3] *NT&D -Nanotechnology and Devices, Germany*
[4] *FOM Institute DIFFER, The Netherlands*

Transmission Grating Spectrometer for EUV Source Characterization from the UV to the EUV (S52)

H.M.J. Bastiaens[1], C. Bruineman[2], B. Vratzov[1,3], and F. Bijkerk[1,4]
[1] *MESA+ Institute for Nanotechnology, University of Twente, The Netherlands*
[2] *Scientec Engineering, The Netherlands*
[3] *NT&D -Nanotechnology and Devices, Germany*
[4] *FOM Institute DIFFER, The Netherlands*

Comparison of ns vs ps Laser Assisted Vacuum Arc EUV Source (S53)

Girum A. Beyene[1], Enda Scally[1], Patrick Hayden [1], Larissa Juschkin[2], Vasily S. Zakharov[3], Sergey V. Zakharov[3], Padraig Dunne [1], Gerry O'Sullivan[1] and Fergal O'Reilly [1]
[1] *School of Physics, University College Dublin, Ireland,*
[2] *Department of Physics, RWTH Aachen University, Germany*
[3] *EPPRA sas, Villebon sur Yvette, France*

Topic: Applications of EUV Sources

Fast Rigorous Model for Mask Spectrum Simulation in EUV Lithography (S11)

Xiaolei Liu[a,b], Xiangzhao Wang[a], Sikun Li[a], Guanyong Yan[a,b], Andreas Erdmann[c]
[a] *Laboratory of Information Optics and Opt-Electronic Technology, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*
[b] *Graduate School of the Chinese Academy of Sciences, Beijing 100039, China*
[c] *Fraunhofer Institute of Integrated Systems and Device Technology, Schottkystrasse 10, 91058 Erlangen, Germany*

Topic: Modeling

Hydrodynamics Modeling of Liquid Droplet Deformation with Laser Pulses (S44)

I. Yu. Vichev[1, 2], V. G. Novikov[1, 2], V. V. Ivanov[1, 3], V. V. Medvedev[3, 4], V. M. Krivtsun[1, 3], K. N. Koshelev[1, 3], A. M.Yakunin[5], A. Bratchenia[5], V. Banine[5]
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[2] Keldysh Institute of Applied Mathematics RAS, Moscow, Russia
[3] Institute of Spectroscopy RAS, Troitsk, Russia
[4] FOM Institute DIFFER, Nieuwegein, The Netherlands
[5] ASML, Veldhoven, The Netherlands

RZLINE Code Modeling of Sn Laser-produced Plasma Sources of EUV Radiation (S45)

A.S. Grushin[1,3], D.A. Kim[1,3], V.V. Medvedev[4], V.V. Ivanov[1,2], V. G. Novikov[1,3], V. M. Krivtsun[1,2], A.M. Yakunin[5], V. Y. Banine[5] and K. N. Koshelev[1,2]
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[4] FOM Institute DIFFER, Nieuwegein, The Netherlands
[5] ASML, Veldhoven, Netherlands

Radiative Properties of Krypton Plasma in Water-window Spectral Range (S49)

Vassily S. ZAKHAROV, Sergey Zahkarov
EPPRA sas, Villebon/Yvette 91140, France
Keldysh Institute of Applied Mathematics RAS, Moscow 125047, Russia
NRC Kurchatov Institute, Moscow 123182, Russia

Topic: XUV

“Water Window” Laser-Produced Plasma Sources based on High-Z Alloys

Elaine Long[1], Takamitsu Otsuka[1,2], Bowen Li[1] Gerry O’Sullivan[1], Padraig Dunne[1], Emma Sokell[1] & Fergal O’Reilly[1]
[1]UCD School of Physics, University College Dublin,Belfield, Dublin 4, Ireland
[2]Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), and Optical Technology Innovation Center (OpTIC), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585, Japan

Studies of Mixed Lead-Tin Alloys as Targets for EUV LPP Sources

Enda Scally, Paul Sheridan, Gerry O’Sullivan & Fergal O’Reilly
UCD School of Physics, University College Dublin,Belfield, Dublin 4, Ireland

Tailored Multilayer Optics for New X-ray Source Types

Stephen O'Rourke[1], Markus Krämer[1], Reiner Dietsch[1], David Windt[2], Thomas Holz[1], Danny Weißbach[1]
[1] AXO DRESDEN GmbH, 01237 Dresden, Germany
[2] Reflective X-Ray Optics LLC, New York, NY 10027, USA

Wednesday, November 6, 2013

8:30 AM Announcements

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

Announcements
Padraig Dunne (UCD)

8:40 AM Session 7: Keynote Session - 2

Session Chair: Padraig Dunne (UCD)

Coherent X-Rays from Tabletop Femtosecond Lasers and Applications in Nanometrology (S1)
Margaret Murnane
University of Colorado, Boulder, CO

9:20 AM Session 8: XUV

Session Dedicated to the Memory of Prof. Alan Michette

Session Co-Chairs: Takeshi Higashiguchi (Utsunomiya University) and Klaus Mann (Laser-Laboratorium Göttingen)

Efficient Light Sources at BEUV & Water Window Soft X-ray Wavelengths (S41) (Invited)
Takeshi Higashiguchi[1], Yuhei Suzuki[1], Masato Kawasaki[1], Hayato Ohashi[1], Nobuyuki Nakamura[2], Ryoichi Hirose[3], Takeo Ejima[3], Weihua Jiang[4], Taisuke Miura[5], Akira Endo[5], Chihiro Suzuki[6], Kentaro Tomita[7], Masaharu Nishikino[8], Shinsuke Fujioka[9], Hiroaki Nishimura[9], Atsushi Sinahara[10], Daisuke Nakamura[7], Akihiko Takahashi[7], Tatsuo Okada[7], Shuichi Torii[11], Tetsuya Makimura[11], Bowen Li[12], Padraig Dunne[12], and Gerry O'Sullivan[12] *[1]DEEE & CORE, Utsunomiya University*
[2]Institute for Laser Science, The University of Electro-Communications
[3] Institute of Multidisciplinary Research for Advanced Materials, Tohoku University
[4]Nagaoka University of Technology [5]HiLASE Project, Institute of Physics AS
[6]National Institute for Fusion Science [7]Kyushu University, Japan
[8]Japan Atomic Energy Agency [9]Institute of Laser Engineering (ILE), Osaka University

[10]Institute of Laser Technology (ILT) [11]Institute of Applied Physics, University of Tsukuba
[12]School of Physics, University College Dublin

A Tunable Source of Quasi-Phase-Matched Coherent EUV Radiation (S23)
Kevin O'Keeffe, David Lloyd, Simon Hooker
Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, United Kingdom

Complete Spatial Characterisation of EUV Harmonic Wavefronts (S22)
David Lloyd, Kevin O'Keeffe, Simon Hooker
Clarendon Laboratory, Department of Physics, University of Oxford

Table-top EUV/Soft X-ray Source and Wavefront Measurements at Short Wavelengths (S18) (Invited)
K. Mann, J. O. Dette, F. Kühl, M. Lübbecke, T. Mey, M. Müller, B. Schäfer
Laser-Laboratorium Göttingen e.V., Göttingen, Germany

10:40 AM Break (15 minutes)

10:55 AM Session 9: Metrology

Session Co-Chairs: Reza Abhari (ETHZ) and Paul Sheridan (NewLambda Technologies)

Droplet-based LPP Light Source for HVM Inspection Applications (S36)
Bob Rollinger, Nadia Gambino, Andrea Giovannini, Luna Bozinova, Flori Alickaj, Konrad Hertig, Reza S. Abhari and Fariba Abreau[1]
Laboratory for Energy Conversion, Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland
[1]Adlyte Ltd., Zug, Switzerland

Laser Produced Plasmas using Cryogenic Xe for Actinic Metrology and Inspection Tools (S20)
Mark Tillack and Andrew Effenberger
University of California San Diego, La Jolla, CA

Dynamics of a Laser-assisted Z-pinch EUV Source (S27)
I. Tobin[a], L. Juschkin[b] and J. G. Lunney[a]
[a]School of Physics, Trinity College Dublin, Dublin 2, Ireland.
[b]Department of Physics, RWTH Aachen University, Aachen, Germany.

Influence of an Intensive UV Preionization on Evolution and EUV-emission of the Laser Plasma with Xe Gas Target (S12)
Serguei Kalmykov, Alexey Mozharov, Mikhail Petrenko, Maxim Sasin, and Ruben Seisyan
A. F. Ioffe Physico-Technical Institute of the Russian Academy of Sciences

194021 St.-Petersburg, Russia

Development of Microwave Discharge Plasma for Extreme Ultraviolet Lithography (S10)

Saya TASHIMA, Masami OHNISHI, Waheed HUGRASS[1], Hodaka OSAWA and Sho OE
Department of Electrical and Electronic Engineering, Faculty of Engineering Science, Kansai University, 3-3-35 Yamate-cho, Suita, Osaka 564-8680, Japan
[1]School of Computing and Information Systems, University of Tasmania, Locked Bag 1359, Launceston, Tasmania 7250, Australia

Tunable, High Brightness Lab-Scale Soft X-Ray Photons (S32)

P. Sheridan[1,2], F. O'Reilly[1,2], and K. Fahy[1,2]
[1]NewLambda Technologies Ltd, Science Center North, Belfield, Dublin 4
[2]School of Physics, University College Dublin, Dublin 4

12:40 PM Workshop Summary and Announcements

Workshop Summary and Announcements (S51)
Vivek Bakshi, EUV Litho, Inc.

1:15 PM Workshop Adjourned

1:15 PM Leave for Lunch and Tour (Battle of Boyne)

Thursday, November 7, 2013

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

Coherent X-Rays from Tabletop Femtosecond Lasers and Applications in Nanometrology

Margaret Murnane

University of Colorado, Boulder, CO

Coherent, laser-like, beams of short wavelength light, with wavelength spanning from the UV to keV region, can now be generated by high harmonic upconversion of light from a tabletop-scale femtosecond laser. In recent years, rapid advances in high-order harmonic generation (HHG) process has made this new type of light source a candidate for applications in nanotechnology. We recently demonstrated that the HHG process can generate coherent beams with sub-nm wavelengths, corresponding to photon energies >1 keV. We also demonstrated a host of applications in nanoscience and nanotechnology, including probing the elastic properties of thin films of thicknesses ≈ 10 nm, implementing full-field 2D microscopes with record 22 nm spatial resolution (≈1.6lamda), quantifying how nanoscale energy flow differs from bulk, measuring how fast a material can change its electronic or magnetic state, and finally directly observing for the first time how spin currents can control and enhance magnetization in ultra-thin films.

Looking to the future, HHG sources at wavelengths down to 1 nm will enable both imaging and characterization of < 5 nm structures. A great advantage of HHG sources is the possibility for a wide variety of separate measurements using the same setup. EUV high harmonics are sensitive to magnetic and thermal dynamics and can also be used to directly image a sample via coherent diffractive imaging. Therefore this technique offers the possibility of a unique flexible nanometrology tool capable of a wide variety of imaging and characterization modalities.

Presenting Author

Dr. Margaret Murnane is a Fellow at JILA and a member of the Department of Physics and Electrical and Computer Engineering at the University of Colorado. She received her B.S and M.S. degrees from University College Cork, Ireland, and her Ph.D. degree in physics from the UC Berkeley in 1989, and joined the faculty of physics at Washington State University in 1990.

In 1996, Professor Murnane moved to the University of Michigan, and in 1999 she moved to the University of Colorado. Prof. Murnane's research interests have been in ultrafast optical and x-ray science. Prof. Murnane is a Fellow of the American Physical Society and the Optical Society of America. In 1997 she was awarded the Maria Goeppert-Mayer Award of the American Physical Society, in 2000 she was named a John D. and Catherine T. MacArthur Fellow, in 2004 she was elected to the National Academy of Sciences, and in 2006 she was elected a Fellow of the American Academy of Arts and Sciences.

S2

EUV Lithography: Current and Future Requirements and Options?

Vadim Banine

ASML

EUV lithography has come a long way over the last two decades. All six NXE:3100 EUV systems are in use at customer sites. This enables early development of infrastructure around EUVL for all segments of semiconductor market.

Productivity remains the key challenge for the cost effective introduction of EUV and its further scaling in the future at lower technology nodes.

Starting with historical perspective, mid- and long-term challenges for the productivity, systems overview and source in particular will be reviewed. A view onto the necessary worldwide research activities supporting this EUV extension will be shared and discussed.

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.

S3

Enabling EUVL for HVM Insertion

Mark Phillips

Intel Corporation

Long delays in the roadmap for power output of sources for EUVL exposure tools have caused other suppliers (or potential suppliers) of EUV infrastructure to delay or freeze development efforts. As the complete merging of Cymer and ASML resources to focus on the delivery of a production-worthy LPP source for the NXE:33xx tools bears fruit, we run the risk that the introduction of EUV Lithography in production will be gated by infrastructure that was delayed by uncertainty rather than technical roadblocks. Another contribution to the uncertainty about EUVL insertion has been the long history of successful extensions of 193nm immersion lithography, most recently through the use of multiple patterning techniques. While there may be no hard limit to the transistor density that can be achieved in theory with these techniques, it is important to recognize that the long term benefits of further pattern splits are increasingly limited by accumulated edge-placement errors.

Together, solid progress on EUVL exposure tools and the escalating complexity of multiple patterning with 193i lithography make a compelling case for the need to keep the EUV infrastructure on track to support EUVL insertion in time for the 7nm Logic node. In particular, this requires renewed focus on mask blank defects reduction, high-brightness EUV sources for metrology tools, development and commercialization of EUV pellicles, timely delivery of actinic reticle inspection tools capable of inspecting through a pellicle, and development of EUVL exposure sources with power ~1kW and dramatically improved cost-of-ownership for EUV ecosystem as a whole.

Presenting Author

Mark Phillips is a Senior Principal Engineer in Intel's Logic Technology Development group in Hillsboro, Oregon. After completing a PhD in Physics from the California Institute of Technology, he joined Intel 20 years ago to work on development of the 0.35 micron process node. For the last 10 years, he has been the primary technical interface to Intel's exposure tool suppliers, and has worked on the introduction of every new generation of exposure tool into technology development and manufacturing. In the last few years, Mark has also been responsible for defining the roadmap for the factory automation systems that support Intel's lithography tools, and the introduction of new metrology techniques to support lithography.

S10

Development of Microwave Discharge Plasma for Extreme Ultraviolet Lithography

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and Sho OE

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A microwave discharged produced plasma (MDPP) source is developed to generate 13.5 nm extreme ultra violet (EUV) radiation for applications in photolithography. The microwave frequency is 2.45 GHz, the maximum power is 6 kW and repetition frequency is < 1kHz. The working gas is Xenon at pressure in the range 0.5-1.2 Pa. Radiation in the visible and near UV range is removed with the help of a 100 nm Zr filter. The EUV radiation is reflected using two Mo/Si multilayer mirrors in order to attenuate the residual out of band radiation before measuring the in-band EUV using a Silicon diode. Figure 1 shows the photo of MDPP. The Xe gas is fed in a glass tube with inner diameter 3 mm. The micro wave is injected in cavity, which has TM110 mode. The preliminary experiments show that the MDPP produces pulsed EUV radiation of 3 W/str. for P_{rf} = 3 kW at a repetition frequency of 100 Hz.

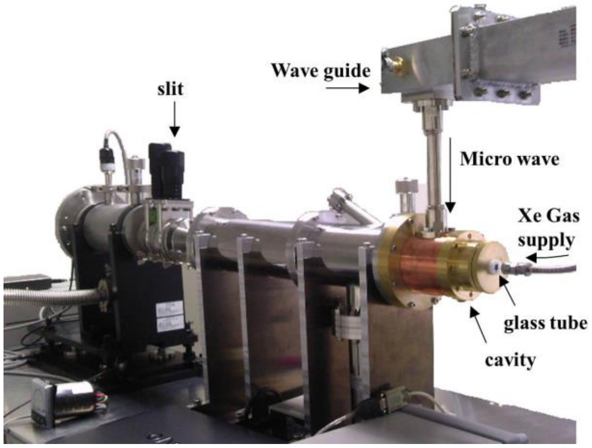

Figure 1 The system of microwave discharge produced plasma system

Presenting Author

Saya Tashima is a postdoctoral at Kansai University. She has background in experimental studies of microwave produced plasma for steady state nuclear fusion from Kyushu University.

S11

Fast Rigorous Model for Mask Spectrum Simulation in EUV Lithography

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A fast rigorous model is built for mask spectrum simulation in EUV lithography. The absorber model is the modified Kirchhoff thin mask model by adding a pulse function to the mask pattern edge. The multilayer model is built by using equivalent layer method. Taking 22 nm space patterns at 6° incident angle as an example, with pattern pitches ranging from 50 nm to 500 nm, the model is 20 times faster while the CD errors of this model are below 0.15 nm and with little fluctuation compared to the rigorous simulation method. Moreover, this fast rigorous model gives an analytical expression of diffraction spectrum of the mask.

Presenting Author

Xiangzhao Wang received his BE degree in electric engineering from Dalian University of Technology, China, in 1982, and his ME and DrEng degrees in electric engineering from Niigata University, Japan, in 1992 and 1995, respectively. Now he is a professor at the Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences. His research interests include lithography imaging theory and technology, information optoelectronics.

S12

Influence of an Intensive UV Preionization on Evolution and EUV-emission of the Laser Plasma with Xe Gas Target

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To enhance emittance of the LPP EUV source with Xe gas jet target, in experiments described main infrared Nd:YAG laser pulse was preceded with that of an ultraviolet KrF excimer laser. The studies were performed at two densities in the target jet – 6×10^{17} cm^{-3} and 6×10^{18} cm^{-3}, approximately. Photography of laser spark forms in the visible range and with a long exposition has been realized, and intensities of the EUV in-band plasma radiation have been measured.

For the most part, the UV prepulse application resulted in an increase of the short-wave radiation output, with its value depending on a delay of the main pulse relative to the prepulse and on focal point locations one relative to another. In the experiments with the lesser density one could get the emission enhancement by a factor of approximately 2.5 but at the higher density the increase was less expressed.

Among observed phenomena, the most surprising one was the fact that the prepulse impact on the target medium persisted for a very long time – up to delays of several microseconds. Influence of the preionization on the plasma ion/energy balance, density waves induced by the prepulse in the gas target, and substantial spreading of the area transparent for the short-wave radiation (a highly enough ionized plasma) are discussed as possible mechanisms to explain this phenomenon.

Presenting Author

Serguei Kalmykov was born March 6, 1939 in Leningrad, Soviet Union. In 1962 he graduated from the Polytechnical Institute (now St. Petersburg State Polythechnical University) and since then he has been a research staff in the Ioffe Institute (St. Petersburg). He is a 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, he was involved into the high temperature plasma and fusion area (general tokamak physics, magnetic confinement, transport processes) but then, in 2007, he moved to the area of laser plasma and EUV source physics. He is author/coauthor of approximately 60 scientific publications.

S13

Microwave EUV Light Sources for Photolithography

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Microwave EUV light source with resonant cavity was developed for the lithographic application. The EUV is emitted from the microwave discharge Xenon plasma, produced in the capillary quarts tube inserted in the resonant cavity filled with TM010 mode of 2.45 GHz microwave. The notable advantages are the compactness, the simple structure, the cheaper cost, above all no debris production over the LPP facilities. The clean EUV are produced by 10W level output (13.5 nm±2% 2πstr) where the pulse repetition is 2 kHz, the magnetron output is 3 kW and the duty is 30%. The EUV power scaling on the gas pressure and magnetron output power will be presented and the extrapolation to the commercial lithographic EUV light source will be discussed at the workshop

Presenting Author

Sho OE is a master course student at Kansai University. He had been experimental studied about micro wave produced plasma for applications in photolithography at Kansai University.

S14

Energy Fraction of CO_2 Laser Absorbed in EUV Source Plasma

Shinsuke Fujioka[1], Teruyuki Ugomori[1], Kensuke Yoshida[1], Chaogang Li[1],
Atsushi Sunahara[2], Katsunobu Nishihara[1], Nozomi Tanaka[1], and
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[1] *Institute of Laser Engineering, Osaka University, Japan*
[2] *Institute for Laser Technology, Japan*

Radiation-hydrodynamics simulation reveals that energy fraction of CO2 laser absorbed in an EUV source plasma is only 50% due to low critical density for CO2 laser light and short density scale length of an EUV source plasma. This small absorption is a crucial problem to limit an energy conversion efficiency from CO2 laser to in-band EUV light, however, its absolute value has never been measured experimentally within the context of EUV light source development.

We are developing an integrating sphere of CO2 laser for this purpose. Absolute energy of laser light scattered by an EUV light source plasma can be measured by using an integrating sphere without considering its angular distribution. Energy fractions of absorbed CO2 laser will be measured for planar and spherical solid targets and a pre-expanded droplet. We will discuss the experimental results in the workshop.

Presenting Author

Shinsuke Fujioka is an Associate Professor in the Institute of Laser Engineering, Osaka University, Japan.

S15

Development of Radiation Hydrodynamic code STAR for EUV Plasmas

Atsushi Sunahara[1], Katsunobu Nishihara[2], Akira Sasaki[3], Nozomi Tanaka[2],
Shinsuke Fujioka[2], and Hiroaki Nishimura[2]

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[2] *Institute of Laser Engineering, Osaka University, Japan*
[3] *Kansai Photon Science Institute, Japan Atomic Energy Agency, Japan*

In order to investigate the efficient emission of Extreme Ultra-violet (EUV) light, the radiation hydrodynamic simulations are indispensable. We have developed the radiation hydrodynamic code STAR. In the conventional EUV light source, the target is firstly irradiated by pre-pulse, and then, the main laser irradiates this pre-formed plasma. In order to simulate the pre-formed plasma accurately, the development of proper hydro-scheme and physical models related to the generation and time evolution of the pre-formed plasma becomes very important. We will show our simulation model developed for STAR. We will also present simulation results of EUV plasmas, and the trial of experimental verification of our simulations.

Presenting Author

S16

Observations of EUV Spectra from Highly Charged Heavy Ions in Optically Thin Plasmas for Benchmarking of Models

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Takeshi Higashiguchi[3], Gerry O'Sullivan[4]

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For EUV lithography beyond 13.5 nm, highly charged lanthanide ions are potentially considered as a light source around 6.x nm. On the other hand, EUV emissions from highly charged ions of bismuth, zirconium, etc. are being investigated for water window light sources in 2.3–4.4 nm for high-contrast biological imaging. Modeling of EUV spectra in laser-produced plasmas is generally challenging due to the effects of line broadening and self-absorption. On the other hand, magnetically confined torus plasmas for fusion research containing highly charged heavy ions can provide optically thin, bright light sources and are a good platform for benchmarking of models because of their low opacity as well as the availability of pellet injection systems and direct electron temperature diagnostics. In this respect, we have observed EUV spectra from such heavy ions in the Large Helical Device (LHD) plasmas at the National Institute for Fusion Science. In relatively low temperature plasmas, narrowed unresolved transition array (UTA) from open N shell ions are clearly observed for $\Delta n=0$ transitions. In higher temperature plasmas, discrete line spectral features are also observed. Interpretations of the observed spectra are presented based on comparisons with theoretical calculations.

Presenting Author

Chihiro Suzuki is an assistant professor at the National Institute for Fusion Science. He received his Ph.D. degree in engineering from Nagoya University. He specializes in optical and spectrometric plasma diagnostics. He is now working on EUV spectroscopy in magnetically confined high temperature plasmas. His recent work is focused on spectroscopy and atomic processes of highly charged heavy ions of interest in fusion and other plasma applications such as EUVL source development.

S17

Modeling of the Laser Plasma Interaction for the Development of Efficient EUV Sources

Akira Sasaki

Quantum Beam Science Directorate, Japan Atomic Energy Agency, Kyoto, Japan

EUV source at λ=13.5nm has been studied toward the realization of next generation microlithography to achieve high output (>200W) with high efficiency (>5%). We investigated the atomic processes in Sn plasma to show efficiency increases at low density where the emission spectrum becomes narrow [1]. New pumping scheme has been proposed by irradiating a small Sn droplet by a weak prepulse laser to produce preformed plasma with an optimized density for EUV emission, where the uniform, low density plasma were heated by the main laser pulse [2]. We investigate methods of modeling hydrodynamics, especially interaction of the low intensity prepulse laser with the solid Sn target. The model takes the phase transition into account and can reproduce fragmentation of the droplet target through the processes of heating, melting evaporation as well as generation of shock wave by prepulse laser irradiation.

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[1] A. Sasaki, et al. J. Appl. Phys. 107, 113303 (2010).
[2] A. Endo, proceedings of the 2013 international workshop on EUV and soft x-ray sources, http://www.euvlitho.com/2012/2012%20Source%20Workshop%20Proceedings.pdf.

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.

S18

Table-top EUV/Soft X-ray Source and Wavefront Measurements at Short Wavelengths

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

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

A compact long-term stable laser-driven plasma source for metrological applications in the extreme UV and soft x-ray range was developed. Based on a pulsed gas jet target, it produces clean radiation in the spectral region from 1 to 20nm, almost without any debris. In dependence of the chosen target gas, both quasi-monochromatic as well as broad-band spectra can be obtained. Comprehensive investigations on the emission characteristics and an improvement of the source brilliance are presented in this contribution, along with performance tests of different types of optical focusing elements (EUV Schwarzschild objective, Kirkpatrick-Baez and ellipsoidal mirrors, Fresnel zone plates). Various applications of the table-top source are described, ranging from material ablation / degradation studies and EUV reflectometry to absorption spectroscopy (XANES, EXAFS) and microscopy in the ´water window´ spectral region.

Moreover, the propagation behaviour of short wavelength radiation is characterized with the help of a Hartmann-type wavefront sensor developed for the EUV/soft x-ray range. In cooperation with DESY / Hamburg this device has been applied for fine-tuning of beam line focusing optics of the free electron lasers FLASH / Hamburg and FERMI / Triest. The wavefront sensor is being employed also for beam and optics characterization of High Harmonic (HHG) and plasma-based sources emitting in the EUV range.

Presenting Author

Klaus R. Mann received his diploma in physics in 1981 and the PhD in 1984 from Univ. of Göttingen, the latter with a thesis written at the Max-Planck-Institut für Strömungsforschung. After a post-doctoral appointment at the IBM Research Ctr. in Yorktown Heights (NY/USA) and work in industry (Alcan Deutschland GmbH) he joined Laser-Laboratorium Göttingen in 1988, where he currently leads the ´Optics / Short Wavelengths´ department.

His research activities cover projects in optics characterization and quality assurance (especially deep UV), laser beam diagnostics and propagation, wavefront analysis, as well as laser-produced plasmas for generation of extreme UV and soft x-ray radiation. He is author of more than 100 scientific publications and also involved in supervision of bachelor, master and PhD students.

S19

BEUV Nanolithography: 6.7 or 11 nm?

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Institute for physics of microstructures of RAS, Nizhny Novgorod, Russia

Recent data on the structural parameters and reflection coefficients of La/B_4C/C mirrors around 6.7 nm are given. The mirrors fabricated by magnetron sputtering. On the basis of these data, an estimation of integral reflectivity of ten-mirror optical systems which is inferior to the theoretical limit by 16 times, is done and the prospects for an increase in the reflectivity of more than an order of magnitude remain uncertain. For minimizing the risks we believe that one has to think about alternatives to BEUV lithography at 6.7 nm. A prospective move to 10.5 and 11.2 nm wavelengths, as an alternative to 6.7 and 13.5 nm, for next generation nanolithography is discussed. Ten-mirror optical systems based on Ru/Be, Mo/Be, Rh/Sr, Mo/Si, and La/B multilayers were compared for efficiency at their working wavelengths. It is shown that the highest performance of a lithography process one may expect with Ru/Be optics and Xe-source optimized for generation around 11 nm. Suggestions for further investigations, which have to be done before implementation the large-scale research to clarify the prospects of the BEUV lithography in the vicinity of 11 nm, are discussed.

Presenting Author

Nikolai Ivanovich Chkhalo holds a doctor of physical and mathematical sciences and is the head of the laboratory.

The areas of his scientific interests are the physics and diagnostics of multilayer structures for X-ray optics; application of the multilayer optics in physical experiments and scientific instrument making, surface science, nanolithography and X-ray microscopy. He is currently involved in the development of methods for diagnostics and studying of physical processes in multilayer structures; development, manufacturing and characterization of optical elements and systems for nanometer-scale resolution short wavelength optics for the projective XEUV nanolithography and X-ray microscopy.

S20

Laser Produced Plasmas using Cryogenic Xe for Actinic Metrology and Inspection Tools

Mark Tillack and Andrew Effenberger

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Although Nd:YAG laser-produced xenon provides a lower achievable conversion efficiency than tin, the lower power requirement for inspection tools makes this a viable option having reduced concerns over debris accumulation. To support the development of a commercial system for actinic metrology, we have explored issues related to cryogenic target formation, laser interactions with frozen Xe in a planar geometry, and especially the effect of pulse length on in-band emissions. The use of frozen xenon creates additional difficulties controlling the density, uniformity and reproducibility of targets as compared with liquid or solid tin. After exploring several process parameters, we were able to obtain relatively reproducible fully-dense surfaces using a nozzle placed near an actively cooled cryogenic target surface. Using a simple optical pulse stretcher, 1064 nm laser pulses with ~30 ns FWHM were compared with unstretched pulses of ~15 ns pulse length. In-band conversion efficiency was observed to drop by only ~20% with longer pulses, which is consistent with our earlier work on tin targets using both Nd:YAG and CO_2 lasers. This result again demonstrates that laser systems with longer pulse length (and lower cost) are preferred.

Presenting Author

Mark Tillack is a research scientist and lecturer at the University of California San Diego in the Mechanical and Aerospace Engineering Department, and associate director of the UCSD Center for Energy Research. He has worked on fusion energy technology for over 30 years, and applications of laser-produced plasmas for the past 10. He is a fellow of both the Institute of Electrical and Electronics Engineers and the American Nuclear Society.

S21

Update of High CE, High Power HVM LPP-EUV Source Development

Hakaru Mizoguchi[1], Hiroaki Nakarai[2], Tamotsu Abe[2], Takeshi Ohta[2],
Krzysztof M Nowak[2], Yasufumi Kawasuji[2], Hiroshi Tanaka[2], Yukio Watanabe[2],
Tsukasa Hori[2], Takeshi Kodama[2], Yutaka Shiraishi[2],Tatsuya Yanagida[2],
Tsuyoshi Yamada[2], Taku Yamazaki[2] ,Shinji Okazaki[1] and Takashi Saitou[2]

[1]Gigaphoton Inc. Oyama facility, JAPAN
[2]Gigaphoton Inc. Hiratsuka facility, JAPAN

We have been developing CO_2-Sn-LPP EUV light source which is the most promising solution as the 13.5nm high power light source for HVM EUVL. Unique original technologies such as; combination of pulsed CO_2 laser and Sn droplets, dual wavelength laser pulse shooting and mitigation with magnetic field have been developed in Gigaphoton Inc..

The theoretical and experimental data have clearly showed the advantage of our proposed strategy. Based on these data we are developing first practical source for HVM; “GL200E”. This data means 250W EUV power will be able to realize around 20kW level pulsed CO_2 laser. We are preparing high average power CO2 laser cooperate with laser supplier.

We report engineering data from our test tools such as 15W average clean power, CE=1.5%, 100kHz operation.

Presenting Author

Dr. Hakaru Mizoguchi is Director and CTO of Gigaphoton Inc.

S22

Complete Spatial Characterisation of EUV Harmonic Wavefronts

David Lloyd, Kevin O'Keeffe, Simon Hooker

Clarendon Laboratory, Department of Physics, University of Oxford

Characterising the spatial and temporal properties of EUV light sources is of fundamental importance for many applications. Knowledge of the wavefront, beam size and coherence not only reveals aspects of the source, but also allows us to evaluate the suitability of the radiation for techniques ranging from microscopy to materials processing. In this talk we describe a new method capable of measuring, in a single scan, the spatial phase profile, beam size and degree of spatial coherence of a EUV light source. The variation of these properties with photon energy is also discussed.

We use a scanning diffracting aperture to effect beam characterisation. The combination of a horizontal slit with an "x"-shaped aperture appears as a pinhole pair for the impinging light. Scanning the "x"-aperture vertically changes the pinhole separation and it is from the recorded interference patterns that the beam properties are recovered. This technique has been named Scanning Interference Technique for Integrated Transverse Analysis of Radiation (SCMITAR)[1].

We have demonstrated this technique by characterising for the first time the complete spatial properties of high harmonic generation, in the wavelength region 13-35nm. The simplicity of the technique lends itself to a wide variety of light sources, both coherent and incoherent, as well as a range of photon energies.

1. Lloyd, D. T., O'Keeffe, K., & Hooker, S. M. Complete spatial characterization of an optical wavefront using a variable-separation pinhole pair. Optics Letters, 38(7), 1173 (2013).

Presenting Author

David graduated from Imperial College London in 2010 with a first class degree in physics. His master's thesis was on the power scaling of solid state lasers under the supervision of Prof. Mike Damzen. He is currently a doctoral student at the University of Oxford in the Atomic and Laser sub department, where he is supervised by Prof. Simon Hooker. David's research interests include the generation and characterisation of EUV light sources.

S23

A Tunable Source of Quasi-Phase-Matched Coherent EUV Radiation

Kevin O'Keeffe, David Lloyd, Simon Hooker

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High-harmonic generation (HHG) is an attractive source of coherent radiation at EUV and soft x-ray wavelengths. However, a significant drawback of HHG is that it is inefficient due to the difference in the phase velocities of the driving and generated radiation. Increasing the flux of HHG sources represents a key challenge if these compact ultrafast sources are to be used in applications such as high resolution imaging or to support the development of future lithographic devices.

Recent experiments to increase the flux of a HHG source via quasi-phase-matching (QPM) are discussed. A train of counter-propagating pulses is used to periodically suppress HHG in regions where the locally generated radiation is out-of phase with the harmonic beam, resulting in an increase of the harmonic intensity. The pulse-trains are generated using a new technique in which the width and separation between pulses can be varied continuously. It is shown that by varying the separation between pulses it is possible to tune the wavelength range over which QPM is achieved, with an order of magnitude increase in the HHG flux being recorded at a wavelength of 24 nm.

Presenting Author

Kevin O'Keeffe completed his undergraduate studies in physics at the National University of Ireland, Cork. He conducted his doctoral research at the Photonics Institute at the Technical University of Vienna, where his research was primarily focused on photo-ionization using few-cycle laser pulses. He is currently a postdoctoral researcher at the Department of Physics at Oxford University. His interests are in the development of high-flux HHG sources and their application to soft x-ray imaging.

S24

Development of High Brightness and High Average Power Picosecond Thin Disc Laser for Short Wavelength Light Sources in HiLASE Project

Taisuke Miura[1], Michal Chyla[1,2], Martin Smrž[1], Siva Sankar Nagisetty[1,2], Patricie Severová[1,2], Ondřej Novák[1], Pawel Sikocinski[1,2], Akira Endo[1], and Tomáš Mocek[1]

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[2]Czech Technical University in Prague, Břehová 7, 115 19, Prague, Czech Republic

One of the research programs in the HiLASE project is aiming to achieve the average power of 500-W with the pulse duration of 1-2 picosecond at the repetition rate of 1-kHz and 100-kHz. The laser sources noted above are based on thin disk technology, sine major applications in the short wavelength light sources, e.g. pre-pulse for dispersion of droplet target, micro plasma for metrology sources, higher harmonics generation, RF photocathode illumination, require high beam quality to realize minimal spot size.

Seed pulse generated from a mode-locked fiber laser is stretched by a compact bulk type pulse stretcher and amplified by a regenerative amplifier which contains an Yb:YAG thin disk and a water-cooled Pockels cell. The Yb:YAG thin disk is pumped by a wavelength-stabilized laser diode at the zero-phonon-line wavelength (969-nm). We have obtained the 50-W average power at the repetition rate of 100-kHz. Also, the output energy at the repetition rate of 1-kHz has been achieved to 45-mJ by the high energy thin disk regenerative amplifier (HERA). The M^2 of output beam in horizontal and vertical directions were 1.25 and 1.23, respectively. And the rms pointing stability was 3.8-μrad.

Presenting Author

Taisuke Miura is a senior researcher of the HiLASE Project. He received his Ph.D. in engineering from Keio University. His present research activities are focused on high power ultrashort pulse generation based on Yb-doped thin disk laser technology.

S25

A Systematic Study of Colliding Plasmas for EUVL

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In the field of EUVL it is well known that emission resulting from pre-heated plasmas can exceed that of the combined emission of plasmas formed by the two individual pulses [1]. It is also known that a colliding interaction between two laser-produced plasmas can result in a stagnation layer that makes a good target for reheating with a subsequent laser pulse [2]. The electron density and temperature of stagnation layers can also be varied easily by changing the parameters of the two colliding plumes. The length of the stagnation layer has also been found to be homogeneous and to have a spatial density distribution that remains relatively flat for many tens of ns [3]. As the stagnation layer created upon the collision of certain plasmas is also a cool plasma it could be used as a target for a delayed secondary CO_2 pulse. These properties make such plasmas potential sources for EUVL. We present results of a systematic study of the appropriateness of colliding plasmas, created with a Nd:YAG laser pulse and reheated with a subsequent CO_2 pulse, for EUVL sources.

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[2] T J Kelly, P Hayden, S S Harilal, J P Mosnier, P Hough, C McLoughin and J T Costello. *J. Phys. D: Appl. Phys.*, **42** 055211 (2009).
[3] J T Costello and J Dardis *Spectrochimica Acta Part B*, **65** 627–635 (2010).

Presenting Author

Dr Emma Sokell obtained her PhD in 1995, from the University of Manchester, for experimental studies of photoionization processes in atoms and small molecules. After post-doctoral work in Manchester, Tokyo (Japan Society for the Promotion of Science Postdoctoral Fellowship) and Toulouse (Centre International des Etudiants et Stagiaires (CIES) fellowship), she took up a lecturing position in UCD in 1999. She has been a Senior Lecturer since 2005. Her research interests remain in the study of the interactions between light and matter and cover a range of areas, from synchrotron based fundamental atomic structure measurements to the study of laser and discharge produced plasmas for EUV and soft x-ray production.

S27

Dynamics of a Laser-assisted Z-pinch EUV Source

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Time and space-resolved optical emission spectroscopy and Langmuir ion probes were used to study the plasma dynamics of a laser-assisted Z-pinch EUV source. The discharge was between two liquid metal coated electrodes and was driven from a 0.39 μF capacitor bank with a maximum voltage of 6 kV. The discharge was triggered by laser ablation of one of the rotating electrodes with a 12 mJ, 30 ns, 1064 nm laser pulse. The source was developed at Russian Institute of Spectroscopy and is based at UCD Dublin. Recently we compared EUV output for tin and galinstan electrodes[1]. In this paper we mainly focus on the analysis of the optical emission before, and after the Z-pinch, where the EUV emission occurs. In the wavelength region of interest (380 - 610 nm) the main line emission is due to Sn II, Sn III and Sn IV. The evolution of the plasma temperature and density is determined using spectral line intensity ratios and Stark broadening, respectively.

[1] I. Tobin et al., Appl. Phys. Lett. **102**, 203504, (2013).

Presenting Author

Isaac graduated with a BSc in Physics Technology from Dublin Institute of Technology in 2009. After that he joined the Laser and Plasma Applications group in Trinity College Dublin as part of a collaborative project with UCD and DCU on the development and study of an efficient source of EUV light. His work has focused on the study of laser triggered discharges and micro Z-pinches as sources of EUV emission.

S28

Design of Freestanding Film Elements for HVM tools of EUV Nanolithography

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Thin metal films are frequently used in experiments on the studying of EUV sources as filters for preliminary spectral selection. The placing of large-aperture thin film filters inside HVM tools of projection EUV lithography has been actively discussed till recent time. The technique for fabrication of large-aperture freestanding multilayer has been developed. Tests of its ability to withstand heat load were fulfilled for freestanding structures of various compositions, showing that $Mo/ZrSi_2$ multilayer film with $MoSi_2$ protective coatings is most stable at high temperatures. The samples of 160 mm in diameter spectral purity filters (SPF) with the transparency about 70% at $\lambda = 13$ nm were demonstrated. However, insufficient strength of thin films together with current progress in development of alternative solutions for spectral filtration restrains the usage of such SPF in industrial nanolithography.

There is still an interest to application of thin films as pellicles for reticle protection. Possible use of rather compact filter between a wafer with photoresist and projective optics chamber is also under consideration. The main purpose of the film element placed here is to suppress contamination of imaging optics by the products of resist outgassing. To the present time the prototypes of $Mo/ZrSi_2$ pellicles up to 80 mm in a diameter were fabricated with a transparency of 84%. Potentiality of fabrication of several compact filters by simultaneous gluing of several frames to stretched freestanding multilayer of large diameter was shown.

Presenting Author

Alexey Lopatin graduated from Nizhny Novgorod State University in 1995. Since then he is a research fellow at Institute for Physics of Microstructures RAS, the department of multilayer optics. For a number of years he has worked on the upgrade of technique for fabrication freestanding multilayers towards larger apertures, better performance and reliability. He is a co-author of several articles on this topic in peer-reviewed journals dated from 2003 to present time.

S29

The Energetiq EQ-10 EUV Source for metrology - Review of Recent Data

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Mask infrastructure is second only to scanner source power as a gating factor for high-throughput EUV lithography. Actinic inspection of mask blanks and aerial image analysis of patterned masks, are key near-term metrology challenges.

The Energetiq EQ-10 EUV source is in use today in several metrology and resist evaluation tools. Evolution in the design of the metrology tools, and early experience with prototypes, is leading to a re-evaluation of source requirements. We will present source data relevant to lifetime, brightness, and stability.

The EQ-10 has applications at shorter wavelength as well. We will present data on operation at 6.7 nm (for advanced EUV R&D) and at 2.88 nm, where the source is in use as a synchrotron replacement for water window microscopy.

Presenting Author

S30

Collector Development with IR Suppression and EUVL Optics Refurbishment at RIT

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Suppression of 10.6μm radiation reflected from LPP is one of the challenging tasks in the source development for EUVL. The following three major approaches are currently used: 1) Transparent Filters (TF), 2) quarter wavelength Anti Reflection Coatings (ARC), 3) Gratings. Both TF and ARC achieved ~99% suppression of 10.6μm radiation with ~30% loss of EUV light at 13.5nm. In this paper we will report a progress on developing a full size (>400mm in diameter and NA~0.2) water cooled collector with a phase grating formed by a diamond turning. Measured suppression of 10.6μm radiation exceeds 99% when loss of 13.5nm light is less than 10%.

Another important research area in EUVL optics development is an optics refurbishment. It is especially important for collector optics, first mirrors of illumination optics and optics used in a closed proximity to exposed wafers coated with a photo resist. We will present our recent results on multi cycle refurbishment of EUV mirrors deposited on silicon substrates. Developed at RIT wet etching and reactive ion etching technologies allow us to re-deposit multilayer optics with a minor (1% - 2%) loss in EUV reflectivity.

Presenting Author

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.

S31

EUV Optical Elements with Enhanced Spectral Selectivity for IR Radiation

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We report on the development of multilayer based solutions to enhance the spectral purity of EUV light generated by plasma-based sources. These multilayer systems reflect EUV radiation and simultaneously suppress infrared (IR) light, e.g. scattered CO_2 laser radiation of the laser-produced plasma. Two possible solutions are discussed: 1) the planar mirrors combining EUV-reflective properties of multilayer Bragg reflectors together with IR antireflection based on the effect of destructive interference; 2) hybrid multilayer gratings combining EUV reflection with spectral-selective suppression of the specular IR reflectance due to the grating phase-shift resonance. Review of experimental results is given for 13.5 nm optics and 6.x nm optics relevant for EUV lithography and beyond.

Presenting Author

S32

Tunable, High Brightness Lab-Scale Soft X-Ray Photons

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NewLambda Technologies offers STAN™, a revolution in soft X-ray sources. The demand for a broadband soft X-ray source comes from varied fields such as fundamental photoelectron spectroscopy, UPS/SXPS/PEEM, reflectometry, nanopatterning, nanoablation, nano-mass spectroscopy, soft x-ray/EUV microscopy, EUV mask inspection and EUV resist exposure, to name a few.

The STAN™ system consists of a laser plasma soft x-ray source, brought to a debris free focus by our plasma robust self-healing liquid metal coated optics. The laser optics are protected by our simple and effective Permanent Clarity™ technology, which allows us to produce tiny laser plasmas continuously on bulk liquid materials, without requiring any complex operation training and at a low cost of operation.

Due to the low etendue of the STAN™ system the photons can be efficiently delivered to the required application. For monochromatic radiation the source can be coupled to a custom built monochromator achieving a bandwidth of < 0.15%, an image size after the exit slit of 50 µm x 50 µm and a divergence at exit of 6.2 mrad (horizontal) x 3.5 mrad (vertical).

The performance of the source is presented along with Xenon Auger spectroscopy data generated utilising the STAN™ source.

Presenting Author

Paul Sheridan is a founding member of NewLambda Technologies. He received his Ph.D. in 2008 in Double Photoelectron Spectroscopy of Strontium, which gave him several years of experience in the joys and pains of synchrotron based research at Bessy, Daresbury and Elettra. At NewLambda Technologies he has been the driving force behind the engineering and systems development of their light sources, from vacuum systems design to source output optimisation and testing. 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.

S33

Modeling of Physical Processes in Plasma-based Sources of EUV Radiation

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We report on the development of methods for the numerical modeling of plasma-based sources of EUV radiation. The developed numerical methods are applied here to describe physical processes in laser-produced plasma (LPP) sources for lithographic. Three important aspects of LPP source operation are considered:

I. Deformation of Sn droplet targets by laser pre-pulse, which is modeled with hydrodynamics OpenFOAM code in combination with RZLINE plasma code.
II. EUV light generation by Sn plasma driven by laser radiation, which is modeled with RZLINE plasma code.
III. Sn plasma expansion in a gaseous atmosphere and optics contamination with Sn, which is modeled with a hybrid Monte Carlo/gas-dynamics code.

Presenting Author

S34

LPP Collector Mirrors – Coating, Metrology and Refurbishment

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The EUV source power and the collector lifetime remains one of the main challenges of EUV Lithography moving from current β-tool phase to high-volume manufacturing by mid of this decade. Since the EUVL transition to HVM requires a solid and global EUV infrastructure, Fraunhofer IOF decided to commercialize their R&D work on multilayers for 13.5 nm by founding a spin-off company in 2012. Since more than ten years, Fraunhofer IOF and later optiX fab develop reliable and cost-effective coating and refurbishment technologies of multilayer-based near normal incidence collector mirrors for high-power laser-produced plasma sources.

Different refurbishment technologies range from complete multilayer stripping, re-polishing and re-coating of used collectors to maintaining all or most of the initial multilayer coating. PTB reflectance measurements of refurbished collector mirrors proofed that the initial EUV reflectance at 13.5 nm can be fully recovered without any reflectance loss. The paper summarizes recent LPP collector coating and metrology status and presents the latest state on collector refurbishment techniques.

Presenting Author

S35

Characterization of Metrology Tools and Optical Components for HVM EUV sources

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PTB accompanies the development of EUV lithography with calibration services from the very beginning almost 30 years ago. The development of high-power sources for HVM requires a reliable radiometric characterization of the sources over a very broad spectral range. Using cryogenic radiometers as primary detector standards together with monochromatized synchrotron radiation, detectors like photodiodes as well as complete spectrometers can be calibrated not only at-wavelength, but also regarding their out-of-band response up to the DUV range.

Another challenge is the characterization of the large EUV collector mirrors. Here, PTB is the unique place where measurement services for such large optics are offered. The PTB measurement capabilities for full spatial mapping of large mirrors facilitated the development of mirror refurbishment procedures by the Fraunhofer IOF / optiX fab GmbH, which are necessary for a cost-effective source operation. The characterization of these mirrors is, however, not only challenging because of their size but also because of their large oblique angles of incidence which require polarization resolved measurements.

In this contribution we will discuss examples like in-band power meters and spectrometers. We will present how we address polarization dependent reflectometry using linearly polarized SR and introduce our new instrumentation for polarization resolved measurements.

Presenting Author

S36

Droplet-based LPP Light Source for HVM Inspection Applications

Bob Rollinger, Nadia Gambino, Andrea Giovannini, Luna Bozinova, Flori Alickaj,
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Laboratory for Energy Conversion, Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland
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At the Applied Laser Plasma Science (ALPS) laboratory at the LEC, ETH Zurich we have been developing tin droplet-based laser-produced plasma sources with application in EUV lithography since beginning of 2007. The laboratory comprises three dedicated facilities, which include two LPP sources and one droplet dispenser development facility. ALPS II is equipped with a large capacity droplet dispenser and a high power (kW), high repetition rate Nd:YAG laser. This main source is used as an engineering test stand, where long-term effects (> 8 hours) of source operation are studied. Adlyte is commercializing the new light source. The system can accommodate (high and low power) EUV collectors and integrates an extensive measurement system, which includes EUV monitors, soft X-ray plasma imaging, Faraday cups and Langmuir probes. As a result, the emission and debris characteristics of individual EUV pulses are monitored and logged during operation. Individual droplet tracking in time and space, which is coupled to a droplet positioning and triggering system, increases the pulse-to-pulse EUV emission stability of the source. Recent performance results of long-term operation and future directions will be presented.

Presenting Author

Bob Rollinger is currently a postdoc at the Applied Laser Plasma Science (ALPS) facility in the Laboratory for Energy Conversion, ETH Zurich. He coordinates all projects relating to the development of the EUV source. He completed his MSc in mechanical engineering at the Swiss Federal Institute of Technology Zurich in 2006, with a focus on aerothermodynamics and thermotronics. He received his PhD from the Laboratory for Energy Conversion, ETH Zurich in 2012. His work was entitled "Droplet Target for Laser-produced Plasma Light Sources". His experimental research includes the development of droplet generation systems for EUV sources. His theoretical research interests include modeling of laser-droplet interactions and plasma formation in EUV sources.

S37

Effect of Misalignment in Laser-droplet Interaction on the Three Dimensional EUV Emission and Ion Distribution

Andrea Giovannini and Reza S. Abhari

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The manufacturing technology for the next generation semi-conductor devices will be based on extreme ultraviolet lithography (EUVL) using a laser produced plasma (LPP) as a candidate 13.5nm light source. EUV sources must be stable, energy efficient and meet the power requirements at intermediate focus. One of the main challenges in order to get the maximum CE in a high repetition rate source is to hit head-on all the droplets. In this work an array of Faraday cups and EUV sensors is used to get insight on the plasma plume expansion and emission for droplets hit head-on and misaligned. The experiment gives insight on the dependence between ion and debris dynamics versus EUV dynamics. The quantification of the effects of misalignment is important for the definition of the laser spot versus the droplet diameter. Also an estimation is given of the distance relative to the laser spot that the droplets can be misaligned, in order to maintain a given shot-to-shot stability.

Presenting Author

Andrea Giovannini is PhD Assistant at ETH Zurich, Laboratory for Energy Conversion. He received his MSc in Mechanical Engineering at ETH Zurich.

S38

Fundamental Atomic Process in Source Development for Beyond EUV Lithography and "Water Window" Imaging

Bowen Li[1], Takeshi Higashiguchi[2], Takamitsu Otsuka[1], Weihua Jiang[3], Akira Endo[4], Emma Sokell[1], Padraig Dunne[1], and Gerry O'Sullivan[1]

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Plasma sources with a wavelength down to 3 nm have gained considerable research interest for use in next-generation semiconductor lithography and for other applications, such as biological imaging. For the former, the recent development of La/B_4C mirrors with a reflectivity of 53.6% in a 0.6% bandwidth centered near 6.7 nm has led to Gd and/or Tb based plasmas as potential sources for microchip fabrication for the next generation of EUV lithography beyond 13.5 nm. For the latter, a major challenge is three-dimensional imaging and single-shot flash photography of microscopic biological structures, such as cells and macromolecules, in *vivo*.

We carried out a number of studies to find both the optimum temperature and source conditions. We studied the influence of the dielectronic re-combination (DR) process on plasma balance modeling and found that the DR process is the dominant recombination mechanism in Pd- and Rh-like gadolinium and will influence the ionization balance in a Gd plasma, which suggests that the DR process should be included in theoretical modeling in all future work on BEUVL source plasmas.

From spectral analysis of high-Z plasmas, we demonstrated a potential "water window" source based on the use of a laser produced bismuth plasma, coupled with multilayer mirror optics. An alternative source in this wavelength region is provided by the 3d-4p and 3d-4f emission from third row elements, for example zirconium. We discuss the effects of mirror bandwidth on the development of table-top water window sources based on laser-produced plasma emission combined with reflectance optics and how it can ultimately determine the choice of optimum source material.

Presenting Author

S39

Advances in Modeling of Physical Processes in Plasma-based Sources of EUV Radiation

V.V. Ivanov[1,2], V.G. Novikov[1,3], A.S. Grushin[1,3], I.Yu. Vichev[1,3], D.A. Kim[1,3],
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Presenting Author

S40

Research Review on Plasma-based EUV Sources at RnD-ISAN/EUV Labs

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The presentation summarizes the work of RnD-ISAN and EUV Labs research group on EUV sources of radiation. Experimental results for both discharge-produced plasma (DPP) and laser-produced plasma (LPP) systems are reviewed. Progress in the development of high-power DPP source of 13.5 nm radiation based liquid tin jet-electrodes is reported. Studies of ion energy spectra and ion composition are described for Sn-based LPP driven by pulsed TEA CO_2 laser. Possibility of application of a high-power continuous-wave CO_2 laser as a EUV source driver is discussed as an alternative to the pulsed LPP systems. First experimental studies of Sn LPP driven by long (2 μs) laser pulses are presented. Experimental works on Gd-based LPP sources of EUV are also summarized in the presentation.

Presenting Author

S41

Efficient Light Sources at BEUV & Water Window Soft X-ray Wavelengths

Takeshi Higashiguchi[1], Yuhei Suzuki[1], Masato Kawasaki[1], Hayato Ohashi[1], Nobuyuki Nakamura[2], Ryoichi Hirose[3], Takeo Ejima[3], Weihua Jiang[4], Taisuke Miura[5], Akira Endo[5], Chihiro Suzuki[6], Kentaro Tomita[7], Masaharu Nishikino[8], Shinsuke Fujioka[9], Hiroaki Nishimura[9], Atsushi Sinahara[10], Daisuke Nakamura[7], Akihiko Takahashi[7], Tatsuo Okada[7], Shuichi Torii[11], Tetsuya Makimura[11], Bowen Li[12], Padraig Dunne[12], and Gerry O'Sullivan[12]

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We demonstrate the EUV and soft x-ray sources in the 2 to 7 nm spectral region related to the beyond EUV (BEUV) question at 6.*x* nm and the water window source based on laser-produced high-*Z* plasmas. The emission spectral structure which is related to the energy conversion and collection efficiencies was characterized by tuning the various laser irradiation conditions, resulting in a highest conversion efficiency of 0.8% at 6.7 nm into the bandwidth of 0.6% in the solid angle of 2π sr due to the reduction of the plasma expansion loss. In addition, resonance emission from multiple charged ions merges to produce intense unresolved transition arrays (UTAs), extending below the carbon K-edge (4.4 nm). An outline of a microscope design for single-shot live cell imaging is proposed based on high-*Z* plasma UTA sources. We will discuss the value of *x* in 6.*x*-nm BEUV emission and propose the efficient sources in the water window spectral region.

Presenting Author

Takeshi Higashiguchi is an associate professor at Utsunomiya University. He received his Ph.D. in engineering from Utsunomiya University. His research activities have focused on short-wavelength light sources, hybrid short pulse laser system in mid-IR, and advanced optics for vector wave generation.

S43

2D-Gas Dynamics Transient Modeling of Hot Gas Bubble Formation EUV Source Chamber

V. Konovalov[1,3], V. G. Novikov[1,3], V. V. Ivanov[2,3], K. N. Koshelev[2,3], A. M. Yakunin[4], V. Y. Banine[4]

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The process of tin accumulation in laser generated tin plasma based EUV sources can significantly reduce the lifetime of source. We investigated this process in gas filled chamber with three components single velocity 2D gas dynamics model. It was found that for a reasonable description of transport phenomena, ionization/recombination processes and thermal radiation losses should be included into model. The simulations showed that under certain conditions the hot gas bubble can be formed inside the chamber which can significantly affect optics life-time.

Presenting Author

S44

Hydrodynamics Modeling of Liquid Droplet Deformation with Laser Pulses

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A liquid tin target modification by using laser pre-pulse allows to increase the conversion efficiency up to several times. It is known that the droplet dynamics may be very complicated due to different pre-pulse parameters. To describe the hydrodynamics of droplet expansion a combination of RZLINE and OpenFOAM codes is used. The time and space resolved ablation pressure distribution from RZLINE code is applied to the tin droplet and OpenFOAM code provides 3D simulation of droplet dynamics. The calculation gives the shape of the droplet, its crashing and merging, velocities of fragments in dependence of pre-pulse parameters. As a result the influence of target modification onto source characteristics can be investigated and optimized.

Presenting Author

S45

RZLINE Code Modeling of Sn Laser-produced Plasma Sources of EUV Radiation

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The efficiency of generation of EUV radiation by laser-produced plasmas (LPP) is defined by the effective coupling of the driver laser radiation to Sn target. The application of a laser pre-pulse irradiating Sn droplet targets allows to engineer target geometry: depending on the pre-pulse parameters it is possible to create a disk-like target from a Sn droplet or to crush it into a cloud of micro-fragments. Here we report on modeling of LPP EUV sources utilizing tin disk targets. The modeling was performed by using the RZLINE code — a numerical code for the simulation of EUV emission by hot dense plasmas. The purpose of the simulation is to evaluate the spectral characteristics of the radiation source, conversion efficiency, source size, evaporation rate of the target, energetic, and space distribution of debris (nanoparticles, neutrals, and ions).

Presenting Author

S46

Radiation of Gd and Tb Plasmas in 6.X nm Spectral Region

V. Krivtsun, O. Yakushev, R. Gayazov, D. Abramenko and K. Koshelev

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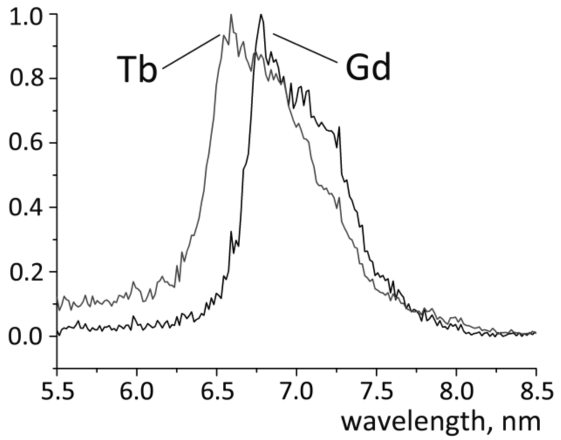
Plasma consisting of multicharged ions of Gd and Tb has been selected as a possible candidate for fuel for Beyond EUV lithography using radiation at 6.X nm. Detailed spectra of these elements excited in DPP and LPP sources have studied in the spectral region of interest. Depending on specifications of MLM one of these elements or their mixture can be used to achieve high power in "in band" (0.6 % - about 0.04 nm) radiation around 6.X nm.



Experimental spectra of Gd and Tb plasmas in the vicinity of 6.X nm exited by focusing of Nd-YAG laser

Comparatively low "in band" CE has been demonstrated for DPP source – below 0.2 % - which most probably eliminates this type of source from further competition. LPP sources were found to be more efficient radiators for both used types of potentially industrial lasers – CO_2 and Nd-YAG. 1,06 um laser with duration of about 20 ns reveals CE between 0.1 – 0.4 % for bulk targets while shortening of a laser pulse down to 1.5 ns allowed to reach CE of about 1 % with a room for further increase in case of specially designed targets.

CO_2 laser experiments with different target geometry and compositions resulted in CE close to 2% which is still lower that a desired value but triggers some optimistic expectations.

Presenting Author

S47

Tailored Multilayer Optics for New X-ray Source Types

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Multilayer mirrors are used for numerous X-ray applications. Most are designed for common tube anode materials (Cu, Mo, Rh, Ag) and respective fluorescence line energies. However, development of new sources especially for the soft X-ray/(V)UV region such as laser plasmas, free electron lasers or special applications at synchrotrons with polarized radiation or energies in the range of few hundred eV leads to a demand for tuned multilayers for those fields. We present a number of special multilayers designed, fabricated and tested in state-of-the-art research, e.g.:

1) Polarization experiments require grazing incidence angles of ~45°, much larger than for total external reflection or typical multilayer mirrors. Here, a multilayer with hundreds of extremely precise layers in the Angström range is necessary. Such mirrors were successfully produced and tested at wavelength in synchrotron experiments.

2) Numerous new X-ray sources in the soft X-ray/(V)UV range have started operation recently and for many applications monochromatizing optics are needed. Apart from production, also simulation and testing of these optics especially below ~100 eV is challenging due to missing optical constants and reliable calibrated sources. We simulated, manufactured and characterized multilayers in this range successfully using various LPP and synchrotron sources showing good agreement with theory.

Presenting Author

S48

Pulsed-power Based Bright EUV Light Source for Metrology

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The actinic metrology tools in EUVL deployment require very stable high brightness EUV sources with moderate in-band power output. We report on a new compact EUV light source development through extensive computational modelling. The source is based on a fast pulsed plasma discharge created in a gas-filled capillary wall confined structure, ignited through a transient hollow cathode discharge mechanism. Nanosecond scale of the resistive discharge is provided by high voltage pulsed power technology with energy storage line imbedded in the source structure. The fast discharge and the dielectric capillary wall confinement provide a small size stably positioned emitting plasma source. The energy storage line is charged to Joule range of electric energy at 20-30kV voltage that provides up to 20kA current through the discharge lasting for 15-20ns. Pulsed plasma of 150nm diameter emits up to 7W/kHz of in-band EUV power into 2π sr. averaged at high frequency operation mode.

Presenting Author

S49

Radiative Properties of Krypton Plasma in Water-window Spectral Range

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Krypton- and zirconium-based plasmas are considered as possible candidates for a source of soft X-ray emission in water window waveband alongside with nitrogen- and bismuth-based radiation plasma sources. Such discharge and laser produced plasmas used in soft X-ray (and EUV) sources are in non-equilibrium state as a rule. This leads to a mismatch between the actual conditions of the plasma and its theoretical/computational estimations because of different effects like self-absorption etc. leading to changes in ionization states, state populations, emission intensity and spectrum. Krypton has a UTA at higher ionization degree than zirconium and thus less preferable but krypton plasma source delivers from debris issues in operation cycle comparing to zirconium and bismuth. Due to wide array of transitions the krypton plasma is less opaque to irradiated emission than nitrogen.

In this paper the radiance and emission properties of non-equilibrium krypton plasma is examined and the optimal emission temperature conditions for soft X-ray emission output in water window region are explored. Kinetic parameters for non-equilibrium plasma including major inelastic ion interaction processes, radiation and emission data are obtained in the approach based on Hartree-Fock-Slater (HFS) quantum-statistical model and distorted waves approximation. The emission spectral efficiency for krypton up to 25% is achieved at 130 eV, comparable to the one for zirconium (40% at 90 eV).

Presenting Author

S50

"Water Window" Laser-Produced Plasma Sources based on High-Z Alloys

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Much effort has gone into the development of plasmas as sources of radiation in the "water window" in recent years [1]. This region of the spectrum, between 2.3 & 4.4 nm, is of interest because of the potential for high-contrast imaging based on the strong absorption by carbon and the low absorption by oxygen. Living tissue in an aqueous environment can thus be imaged with enhanced clarity, providing a useful tool for the life and biomedical sciences.

Using a 180-ps Nd:YAG laser, plasmas were formed on bulk alloy targets made from Fields Metal (Bi 50%, Pb 28% and Sn 22%) an Roses Metal (Bi 57%, In 26% and Sn 17%), with pulse energies ranging from 20 – 340 mJ. Spectra were recorded using a 0.25-m grazing-incidence spectrograph, equipped with a variable groove spacing with 1200 grooves/mm, and a TE cooled CCD camera with 2048 pixels in the spectral direction.

Spectral analysis was carried out with the aid of the atomic structure code of Cowan [2], and the CR plasma model of Colombant & Tonon [3].

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Presenting Author

S51

Studies of Mixed Lead-Tin Alloys as Targets for EUV LPP Sources

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Laser produced plasmas have been heavily researched as sources of EUV radiation for lithography, metrology and reflectometry [1]. Here we present spectra between 9 & 18 nm from plasmas formed on solid alloy targets containing tin, lead, bismuth and indium using a 1064 nm Nd:Yag 5ns laser pulse. Power densities of 5 x 10^9 W/cm^2 to 1 x 10^{12} W/cm^2 were obtained, the effect of both laser spot size and laser input energy on the spectral emission were studied. The spectra were captured using a grazing incidence Jenoptik E-spec EUV spectrograph with a variable line spaced grating. Spectra for pure lead and tin were captured under the same experimental conditions to better understand their contribution to the alloy's spectra.

Analysis of the spectra was aided by calculations performed using the Cowan code [2] and the CR model of Colombant & Tonon [3]. The spectra showed a relatively flat emission across the wavelength region observed, making it a possible candidate for an EUV reflectometry source.

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Presenting Author

S52

Transmission Grating Spectrometer for EUV Source Characterization from the UV to the EUV

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The characterization of the in-band as well as the out-of-band radiation from EUV lithography sources requires measurements at high resolution over a broad wavelength band, ranging from the UV to the EUV. Spectrometers based on high line density transmission gratings offer such high resolution and form powerful tools for source benchmarking from the UV up to and including the EUV band. Here, we report on the development and operation of such a spectrometer. The essential high-resolution grating technology is based on UV-NanoImprint Lithography for the production of series of free standing gratings with up to 10.000 line pairs/mm. This spectrometer uses different gratings to either take high resolution spectra or broad band survey spectra: a grating-filter set selects different bands, while the second order is suppressed by the grating geometry. Alignment of grating and filter is fully automated and remote controlled via a USB interface. Incorporating a large set of gratings with different grating period on one single chip allows for a large working range of the spectrometer spanning the UV to EUV, without the need to break the vacuum. The spectrometer is also provided with a range of precise micropinholes and an automated system for positioning them in front of the grating by which an excellent spectral resolution of down to 0.1 nm is achieved. To monitor the radiation produced by the EUV source, the spectrometer is equipped with a matched high resolution EUV CCD camera. Detailed source spectra from UV to EUV will be shown, as well as a proposal for cross-platform, out-of-band source characterization over the full range from the VIS to the EUV band.

Presenting Author

S53

Comparison of ns vs ps Laser Assisted Vacuum Arc EUV Source

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Plasma based EUV sources have been studied extensively to meet strict requirements on high power & brightness among others. The motivation is to develop a hybrid Laser-triggered Discharge Plasma (LDP) for which: the electrode is regenerative and so erosion is reduced, it is laser-assisted so the required input power is reduced and, it is Sn based which has an intrinsically higher CE in comparison to Xe. The aim of this work is to produce EUV photons from discharge plasma formed by liquid Sn, coated on rotating-disc-electrodes. The discharge was triggered by localized ablation of the thin film with either a ~160ps or ~7ns, 1064nm, Nd:YAG laser, with laser energy varying from 1 to 100mJ.

A comparison of the conversion efficiency (CE) was made, where the ps-triggering resulted in higher CE values compared to ns-triggering. A 2D-RMHD simulation code-Z*[1], was used to understand the expanding plasma dynamics, where the ps-gives a smaller density and hotter plasma and hence higher conductivity, which then facilitates the ohmic heating for an efficient EUV emission during the pinch.

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Presenting Author

Girum A. Beyene, is currently a doing a joint PhD between University College Dublin (Ireland) and RWTH University Aachen (Germany) under Erasmus Mundus European Scholarship. Under the same scheme he got a joint MSc in 2009 in Fusion Plasma Science & Engineering Physics from University of Nancy (France), Royal Institute of Technology (KTH-Sweden) and Research Centre Juelich (Germany), under project involving Laser Induced Desorption / Breakdown Spectroscopy as a plasma-wall interaction diagnostics. His current research area involves laser-plasma interaction experiments towards high brightness short-wavelength light sources.

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