2015 International Workshop on EUV and Soft X-Ray Sources

November 9-11, 2015

Dublin ▪ Ireland

Workshop Abstracts

EUV Litho, Inc.

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2015 International Workshop on EUV and Soft X-ray Sources

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Welcome

Dear Colleagues;

I will like to invite you to the 2015 International Workshop on EUV and Soft X-Ray Sources in Dublin, Ireland.

6th annual source workshop is now the largest annual gathering of EUV and XUV source experts and continues to grow and serve the community. 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. As always, 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, 2015 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 (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)
Chiew-seng Koay (IBM)
Konstantin Koshelev (ISAN)
Rainer Lebert (Bruker)
Peter Loosen (ILT-Fraunhofer)
Eric Louis (University of Twente)
James Lunney (Trinity College, Dublin)
John Madey (University of Hawaii)
Shunko Magoshi (EIDEC)
Hakaru Mizoguchi (Gigaphoton)
Udo Dinger (Carl Zeiss)
Katsuhiko Murakami (Nikon)
Patrick Naulleau (LBNL)
Katsunobu Nishihara (Osaka University)
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)
Emma Sokell (UCD)
Seichi Tagawa (Osaka University)
Hironari Yamada (PPL)
Mikhail Yurkov (DESY)
Sergey Zakharov (NAEXTSTREAM)
Vivek Bakshi (EUV Litho, Inc.) - Organizing Chair
Padraig Dunne (UCD) - Organizing Co-Chair

Workshop Agenda

2015 International Workshop on EUV and Soft X-Ray Sources
(2015 Source Workshop)

Agenda Outline

Monday, November 9, 2015

Location: Newman House, Stephen's Green, Dublin

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

Tuesday, November 10, 2015

Location: George Moore Auditorium, UCD Campus, Dublin

8:30 AM	Bus Pickup at Newman House and Mespil Hotel for UCD Campus
9:15 AM – 12:35 PM	Workshop Presentations
12:35 PM – 2:00 PM	Lunch
2:00 PM – 4:40 PM	Workshop Presentations
4:40 PM	Time off for networking
5:10 – 6:30 PM	Source TWG Meeting (Closed) Location TBA

(Buses will be available to take workshop attendees to downtown after the workshop presentations as well as after the TWG Meeting)

Wednesday, November 11, 2015

Location: George Moore Auditorium, UCD Campus, Dublin

8:30 AM	Bus pickup at the Hotel (Newman House and Mespil Hotel) for UCD Campus
9:15 – 12:35 PM	Workshop Presentations
12:35 PM - 1:40 PM	Lunch
1:40 PM – 4:50 PM	Oral Presentations
5:20 PM – 6:50 PM	Poster Session
7:00 PM	Depart for off-site Dinner

(Buses will be available to take participants to off-site dinner location.)

WORKSHOP AGENDA

2015 International Workshop on EUV and Soft X-Ray Sources

November 9-11, 2015, Dublin, Ireland

Monday, November 9, 2015 (Newman House)

6:00 PM – 7:00 PM Registration, Reception and Speaker Prep

Tuesday, November 10, 2015 (George Moore Auditorium)

9:15 AM Announcements and Introductions

Welcome, Announcements and Introduction (Intro-1)

TBA, *UCD, Dublin*

Vivek Bakshi, *EUV Litho, Inc., USA*

9:35 AM Session 1: Keynote Session -1

Session Chair: Padraig Dunne (UCD)

EUVL Advancements Toward HVM Readiness (S1)

Britt Turkot
Intel Corporation

Performance Overview and Outlook of EUV Lithography Systems (S2)

Wim van der Zande
ASML

Break 10:55 AM (20 Minutes)

11:15 AM Session 2: HVM EUV Sources

Session Co-Chairs: Wim van der Zande (ASML) and Hakaru Mizoguchi (Gigaphoton)

Performance of One Hundred Watt Source and Construction of 250Watt HVM LPP-EUV Source (S12) (Invited)

Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Krzysztof M Nowak, Yasufumi Kawasuji, Hiroshi Tanaka, Yukio Watanabe, Tsukasa Hori, Takeshi Kodama, Yutaka Shiraishi, Tatsuya Yanagida, Georg Soumagne, Tsuyoshi Yamada, Taku Yamazaki, Shinji Okazaki and Takashi Saitou
Gigaphoton Inc. Hiratsuka facility, Hiratsuka Kanagawa, JAPAN

Studies of Laser-produced Tin plasmas for EUV Light Sources using Collective Thomson Scattering (S13) (Invited)

Kentaro Tomita[1], Yuta Sato[1], Toshiaki Eguchi[1], Shoichi Tsukiyama[1], Kiichiro Uchino[1], Tatsuya Yanagida[2], Hiroaki Tomuro[2], Yasunori Wada[2], Masahito Kunishima[2], Takeshi Kodama[2], Hakaru Mizoguchi[2]
[1] *Interdisciplinary Graduate School of Engineering and Sciences, Kyushu University, 6-1, Kasugakoen, Kasuga, Fukuoka 816-8580, JAPAN*
[2] *Gigaphoton Inc., 400 Yokokurashinden Oyama,Tochigi, 323-8558, JAPAN*

Experimental and Theoretical Studies of Tin Droplets Shaping by Picosecond Laser pre-pulses (S24) (Invited)

Slava Medvedev et al
Institute for Spectroscopy, Russian Academy of sciences

Correlation between Laser Absorption Process and Energy Conversion to Extreme Ultraviolet Radiation in Laser Produced Tin Plasma (S16)

Hiraku Matsukuma[1],Atsushi Sunahara[2], Tatsuya Yanagida[3], Hiroaki Tomuro[3], Kouichiro Kouge[3], Takeshi Kodama[3], Tatsuya Hosoda[1], Shinsuke Fujioka[1], and Hiroaki Nishimura[1]
[1] *Institute of Laser Engineering, Osaka University, Suita, 565-0871, Japan*
[2] *Institute of Laser Technology, Suita, 565-0871, Japan*
[3] *Gigaphoton, Inc., 3-25-1, Shinomiya, Hiratsuka 254-8555, Japan*

Lunch 12:35 PM

2:00 PM Session 3: Modeling
Session Dedicated to the Memory of Vladimir G. Novikov

Session Chair: Gerry O'Sullivan (UCD) and A. Sunahara (Osaka University)

In the Memory of Prof. Vladimir G. Novikov (S38)

Slava Medvedev
Institute for Spectroscopy, Russian Academy of sciences

Hydrodynamics Modeling of the Dynamics of Sn droplet Target for the EUV Source (S17)

Akira Sasaki
Kansai Photon Science Institute, Japan Atomic Energy Agency, Kyoto, Japan

Radiation Hydrodynamic Simulation of Laser-produced Tin Plasmas (S20) (Invited)

A. Sunahara[1], H. Matsukuma[2], K. Nishihara[2], and A. Sasaki[3]
[1]*Institute for Laser Technology*
[2] *Institute of Laser Engineering*
[3] *Japan Atomic Energy Agency*

Experimentally Validated Neutral Cluster Debris Mean Velocity and Trajectory Model for Droplet-Based Laser Produced Plasma Sources (S34)

Duane Hudgins, Nadia Gambino, Bob Rollinger and Reza S. Abhari
Laboratory for Energy Conversion, Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland
Adlyte AG, Zug, Switzerland

3:10 PM Break and Group Photograph (20 Minutes)

3:30 PM Session 4: EUV Sources for Metrology

Session Co-Chairs: Klaus Bergmann (Fraunhofer-ILT) and Reza Abhari (ETH)

Bright and Reliable Xe-based EUV Source for Metrology and Inspection Applications (S31) (Invited)

Oleg Khodykin
RAPID, KLA-Tencor Inc.

Discharge based EUV Source for Metrology and Inspection (S32) (Invited)

Klaus Bergmann, Alexander von Wezyk and Jochen Vieker
Fraunhofer Institute for Laser Technology – ILT, Aachen, Germany

High-radiance LDP Source: clean, Reliable and Stable EUV Source for Mask Inspection (S35) (Invited)

Yusuke Teramoto, Bárbara Santos, Guido Mertens, Ralf Kops, Margarete Kops, Hironobu Yabuta, Akihisa Nagano, Noritaka Ashizawa, Takahiro Shirai, Kunihiko Kasama, Alexander von Wezyk[1] and Klaus Bergmann[1]
USHIO Inc.
[1]*Fraunhofer ILT*

Light Sources for High Volume Metrology and Inspection Applications (S37) (Invited)

Reza S. Abhari
ETH Zurich, Switzerland

Break 4:50 PM (20 Minutes)

Adjourn for the day – Time off for Networking

5:10 PM Source TWG meeting (Closed) –Location TBA

End of Day 2

Wednesday, November 11, 2015

9:15 AM Announcements

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

9:25 AM Session 5: Keynote Session - 2

Session Chair: Padraig Dunne (UCD)

Laser Plasma Sources of Soft X-rays and Extreme ultraviolet (EUV) for Application in Technology and Science (S3)

Henryk Fiedorowicz
Institute of Optoelectronics, Military University of Technology, Warsaw, Poland

10:05 AM Session 6: Optics

Session Co-chairs: Joost W.M. Frenken (ARCNL) and Eric Louis (University of Twente)

The Advanced Research Center for Nanolithography (S41) (Invited)

Joost W.M. Frenken
Advanced Research Center for Nanolithography (ARCNL), Science Park 110, 1098 XG, Amsterdam, The Netherlands

Studies of Thermal Transport in Mo/Si Multilayer Structures (S42)

Slava Medvedev
Institute for Spectroscopy, Russian Academy of sciences

EUV and Beyond EUV Optics Research at the University of Twente (S43) (Invited)

Eric Louis, Robbert van de Kruijs, Andrey Yakshin, Johan Reinink, Dmitry Kuznetsov, Ben Wylie van Eerd, Chris Lee and Fred Bijkerk, [1]Hartmut Enkisch and [1]Stephan Müllender
MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE, Enschede, The Netherlands
[1]*Carl Zeiss SMT GmbH, Rudolf-Eber-Straße 2, 73447 Oberkochen, Germany*

11:05 AM Break (20 minutes)

11:25 AM Session 7: XUV Sources

Session Co-chairs: Rainer Lebert (Research Instruments) and Ladislav Pina (CTU)

Identification of Plasma Sources for Water Window Imaging: Recent Spectroscopic Studies (S58) (Invited)

G. O'Sullivan[*], P. Dunne[*], T. Higashiguchi[†], B. W. Li[$], R. Lokasani[*], E. Long[*], H. Ohashi[#], F. O'Reilly [*], P. Sheridan[*], J. Sheil[*], E. Sokell[*], C. Suzuki[+], and T. Wu[*]
[*]*School of Physics, University College Dublin Belfield, Dublin 4, Ireland*
[†]*Department of Advanced Interdisciplinary Science and Center for Optical Research (CORE), Utsunomiya University, Utsunomiya, Tochigi 321-8585 Japan,*
[$]*School of Nuclear Science and Technology, Lanzhou University, Lanzhou, China*
[#]*Graduate School of Science and Engineering for Research, University of Toyama, Toyama, Japan*
[+]*National Institute for Fusion Science,Toki, Gifu 509-5292, Japan*

UCD Physics Overview (10 Minutes) *(S70)*

Gerry O'Sullivan / Padraig Dunne (*UCD)*

Effects of Optical Thickness on Soft X-ray Spectral Feature Observed in Gd and Tb Plasmas (S54)

Chihiro Suzuki[1], Takeshi Higashiguchi[2], Atsushi Sasanuma[2], Goki Arai[2], Yusuke Fujii[2], Thanh Ding Hung[2], Fumihiro Koike[3], Izumi Murakami[1], Naoki Tamura[1], Shigeru Sudo[4]
[1]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*
[2]*Utsunomiya University, 7-1-2 Yoto, Utsunomiya 321-8585, Japan*
[3]*Sophia University, 7-1 Kioi-cho, Chiyoda-ku, Tokyo 102-8554, Japan*
[4]*Chubu University, 1200 Matsumoto-cho, Kasugai 487-8501, Japan*

Laser-Produced Plasma Spectroscopy of Medium to High-Z Elements in the 2 to 9-nm Spectral Region (S55)

Elaine Long[1], Chihiro Suzuki[2], John Sheil[3], Elgiva White[3], Ragava Lokasani[1], Bowen Li[1], Paul Sheridan[1], Patrick Hayden[4], Emma Sokell[1], Padraig Dunne[1], Fergal O'Reilly[1] & Gerry O'Sullivan[1]
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[2] National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan
[3] Summer Intern at UCD School of Physics
[4] National Centre for Plasma Science & Technology and School of Physical Sciences, Dublin City, Dublin, Ireland

12:35 PM Lunch

1:40 PM Session 8: Applications of XUV Sources

Session Co-chairs: Torsten Feigl (optiX fab) and Larissa Juschkin (RWTH)

Multilayer Collector Optics for Water Window Microscopy (S65) (Invited)

Torsten Feigl
optiX fab, Germany

Application of Lens-less Imaging Techniques for Nano-scale Microscopy Employing Plasma-based EUV Source (S64) (Invited)

Larissa Juschkin[1,2], Jan Bußmann[1,2], Michal Odstrcil[3], Raoul Bresenitz[1,2], Denis Rudolf[2]
[1] RWTH Aachen University and JARA— Fundamentals of Future Information Technology, Chair for the Experimental Physics of EUV, Aachen, Germany
[2] Peter Grünberg Institute 9 and JARA— Fundamentals of Future Information Technology, Research Centre Jülich, 52425 Jülich, Germany
[3] Optoelectronics Research Center, University of Southampton, United Kingdom

Laboratory-based Photoemission Spectro-microscopy at 71.7 eV for Studies of Complex Materials (S61)

Daniel Wilson [1,2,4,5], Christoph Schmitz [1,5], Denis Rudolf [2,3,5], Sally Rieß [3,5], Martin Schuck [3,5], Carsten Wiemann [1,5], Astrid Besmehn [6], Hilde Hardtdegen [3,5], Detlev Grützmacher [3,5], Claus M. Schneider [1,5], F. Stefan Tautz [4,5], and Larissa Juschkin [2,3,5]

[1] Forschungszentrum Jülich, Peter Grünberg Institut (PGI-6), Germany
[2] RWTH Aachen University, Experimental Physics of EUV, Aachen, Germany
[3] Forschungszentrum Jülich, Peter Grünberg Institut (PGI-9), Germany
[4] Forschungszentrum Jülich, Peter Grünberg Institut (PGI-3), Germany
[5] Jülich-Aachen Research Alliance (JARA), Fundamentals of Future Information Technology, Germany
[6] Forschungszentrum Jülich, Central Institute for Engineering, Electronics and Analytics (ZEA-3), Germany

Water-Window Microscope Based on Nitrogen Plasma Capillary Discharge Source (S63)

T. Parkman[1], M. F. Nawaz[2], M. Nevrkla[2], M. Vrbova[1], A. Jancarek[2]
[1]Czech Technical University in Prague, Faculty of Biomedical Engineering, 272 01 Kladno, Czech Republic
[2]Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, 180 00 Prague 8, Czech Republic

3:00 PM Survey (ALL) (10 Minutes)

3:10 PM Break (20 Minutes)

3:30 PM Session 9: FEL Sources for EUVL

Session Co-Chairs: Akira Endo (HiLase) and Alexander Chao (SLAC)

Picosecond, kW Thin-disc Laser Technology for LPP and FEL EUV Sources (S21) (Invited)

A. Endo[1,2], M. Smrz[1], O. Novak[1], H. Turcicova[1], J. Muzik[1], J. Huynh[1], T. Mocek[1], K.Sakaue[2] and M.Washio[2]
1) HiLASE Centre, Institute of Physics AS CR, Dolní Břežany, Czech Republic
2) RISE, Waseda University, Tokyo, Japan

Current Progress on Design Work of High Power EUV-FEL based on ERL (S22) (Invited)

Kensei Umemori
High Energy Research Organization (KEK),Tsukuba, Ibaraki, Japan, 305-0801

A Kilowatt Storage Ring EUV Source Based on Steady State Microbunching (S23) (Invited)

Alexander Chao, Daniel Ratner
SLAC National Accelerator Laboratory, Menlo Park, CA, USA

4:30 PM Workshop Summary and Announcements

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

4:50 PM Break (20 Minutes)

5:20 PM Session 10: Poster Session (90 Minutes) (Poster Paper Listing on Following Pages)

7:00 PM Depart for Dinner

5:20 PM Session 10: Poster Session

Session Chair: Padraig Dunne (UCD)

Topic: EUV Sources for HVM

Research of the Tin Droplet Generator and Plume Expansion of Laser Produced Tin Droplet Plasma (S11)

Chen Ziqi, Wang Xinbing and Zuo Duluo
Wuhan National Laboratory for Optoelectronics,
Huazhong University of Science & Technology, Wuhan 430074, China

Research of CO_2 Laser Produced Sn and SnO_2 plasma (S14)

Lan Hui [1,3], Wang Xinbing [2], Zuo Duluo [2], Zhen Guang[3]
[1]*School of Optical and electronic information, Huazhong University of Science and Technology, Wuhan 430074, China*
[2]*Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China*
[3]*School of Physics and information engineering, Jianghan University, Wuhan 430056, China*

Droplet Generator for High Brightness LPP EUV Source (S15)

Alexander Vinokhodov[1], Vladimir Krivtsun[1,2], Mikhail Krivokorytov[1], Yury Sidelnikov[1,2], Viacheslav Medvedev[1,2], Konstantin Koshelev[1,2]
[1] *EUV Labs/RnD ISAN, Moscow, Russia*
[2] *Institute for Spectroscopy RAS, Moscow, Russia*

ARCNL's Laser-produced Plasma EUV Source (S18)

D. Kurilovich, F. Torretti, W. Ubachs, R.A. Hoekstra, O.O. Versolato
Advanced Research Center for Nanolithography, Science Park, Amsterdam

A Study of Colliding Plasma Processes for Elements of Different Mass (S19)

D.Kos[1], O. Maguire[1], P. Oudayer[2], P. Dunne[1], F. O'Reilly[1], and E. Sokell[1]
[1]*School of Physics, University College Dublin, Belfield, Dublin 4, Ireland*
[2]*University of Paris-Sud, 15 Street Georges Clemenceau, 91400 Orsay, France*

Topic: EUV Sources for Metrology

Combination of Discharge and Laser-produced Plasmas for High Brightness Extreme ultraviolet (EUV) Light Sources (S33)

Florian Melsheimer[1,2,3]; Richard Lensing[1,2,3], Girum Beyene[1,2,3,4], Xiaoduo Wang[1,2,5], Larissa Juschkin[1,2,3]
[1]*Experimental Physics of EUV, RWTH Aachen University;*
[2]*Peter Grünberg Institut (PGI-9), Research Centre Jülich GmbH*
[3]*Jara – Fundamentals of Future Information Technology*
[4]*School of Physics,University College Dublin*
[5]*Changchun Institute of Optics, Fine Mechanics and Physiks, University of Chinese Academy of Sciences)*

Tin Droplets for EUV Sources (S36)

Alexander Sanders, Bob Rollinger, Nadia Gambino, Duane Hudgins, Markus Brandstätter, Marco Weber and Reza S. Abhari
Laboratory for Energy Conversion
Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland

Plasma Design of the EQ-10 EUV Source (S38)

Stephen F. Horne, Matthew J. Partlow, Deborah S. Gustafson, Matthew M. Besen, Donald K. Smith, Paul A. Blackborow
Energetiq Technology Inc., 7 Constitution Way, Woburn MA 01801 USA

Topic: XUV Sources

Feature of Unresolved Transition Array Emission in Water Window Soft X-ray Spectral Region from a Dual-pulse Laser-produced Bismuth Plasma (S51)

Hiroyuki Hara, Goki Arai, Thanh-Hung Dinh, and Takeshi Higashiguchi
Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), Utsunomiya University, Utsunomiya, Tochigi 321-8585 Japan

Laser-produced Multiply Charged Ion Plasma Sources for a Compact Water Window Soft X-ray Microscope (S52)

Yoshiki Kondo[1], Thanh-Hung Dinh[1], Goki Arai[1], Takeo Eijima[2], and Takeshi Higashiguchi[1]

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[2] *Institute of Multidisciplinary Research for Advanced Materials (IMRAM), Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai, 980-8577 JAPAN*

Absorption Spectral Structure in Highly-charged Zirconium Plasmas in Water window Soft X-ray Spectral Region (S53)

Takanori Miyazaki[1,2], Goki Arai[2], Hiroyuki Hara[2], Thanh-Hung Dinh[2], Takeshi Higashiguchi[2], Akinobu Irie[2],
Chihiro Suzuki[3], Daiji Kato[3], Akira Sasaki[4], Padraig Dunne[1], and Gerry O'Sullivan[1]
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[4]*Quantum Beam Science Center, Japan Atomic Energy Agency, 8-1-7 Umemidai, Kizugawa, Kyoto 619-0215, Japan*

Experimental Study of the Interaction of Sub-nanosecond and Nanosecond Duration Laser Pulses with Solid Targets at Different Laser Energies (S56)

Ragava Lokasani[1, 2], Elaine Long[2], Oisin Maguire[2], Domagoj Kos[2], Paul Sheridan[2], Patrick Hayden[2], Fergal O'Reilly[2], Padraig Dunne[2], Emma Sokell[2], Akira Endo[3], Jiri Limpouch[1] and Gerry O'Sullivan[2]
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[3]*Institute of Physics of Academy of Sciences of the Czech Republic, HiLase Center, Za Radnici 828, 252 4, Dolni Brezany, Czech Republic*

Colliding Laser - produced Plasma Experiments on Carbon Group Elements (S57)

O. Maguire[1], D. Kos[1], P. Oudayer[2], P. Dunne[1], F. O'Reilly[1], T. McCormack[1] and E. Sokell[1]
[1]*UCD School of Physics, University College Dublin, Dublin 4, Ireland*
[2]*University of Paris-Sud, Orsay, France*

Efficient EUV Sources by Short CO_2 Laser-produced Plasmas (S59)

Atsushi Sasanuma[1], Reiho Amano[1], Thanh-Hung Dinh[1], Goki Arai[1], Takeshi Higashiguchi[1] and Taisuke Miura[2]

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[2]HiLASE Centre, Institute of Physics ASCR, v.v.i.,Dolni Brezany, Czech Republic

ABSORPTION OF EUV RADIATION IN MATTER AND RELATED PROCESSES (S66)

Chiara Liberatore[1], Klaus Mann[5], Matthias Müller[5], Andrzej Bartnik[6], Inam Ul Ahad[6],Ladislav Pina[3], Libor Juha[4], Ludek Vyšín[4], Jorge J. Rocca[7], Akira Endo[2] and Tomas Mocek[2]

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ABSTRACTS

S1

EUVL Advancements Toward HVM Readiness

Britt Turkot

Intel Corporation

This past year has witnessed a sharp increase in EUV lithography progress spanning production tools, source and infrastructure to better position the technology for HVM readiness. While the source remains the largest contributor to downtime and availability, significant strides in demonstrated source power have bolstered confidence in the viability of EUVL for insertion into HVM production. The commitment by ASML to deliver an EUV pellicle solution alleviates industry concern about one significant source of line-yield risk, and while industry support for actinic patterned mask inspection (APMI) has waned, renewed development efforts focus on alternative approaches.

In addition to continued expected improvements in EUV source power and availability, the ability to deliver predictable yield remains an ultimate gate to HVM insertion. To ensure predictable yield requires significant emphasis on reticles: with continued pellicle development to ensure the readiness and supply of a robust pellicle solution in advance of 250W source power, as well as improvements in mask blank defectivity and techniques to detect and mitigate reticle blank and pattern defects.

Presenting Author

Britt Turkot is a senior principal engineer and engineering group leader with Intel's Portland Technology Development Lithography organization where she is the EUV program manager for Intel. She has been with Intel since 1996 after receiving B.S., M.S. and Ph.D. degrees in Materials Science and Engineering from the University of Illinois at Urbana-Champaign.

S2

Performance Overview and Outlook of EUV Lithography Systems

Wim J. van der Zande

ASML Netherlands B.V., De Run 6501, 5504 DR Veldhoven, The Netherlands

Multiple NXE:3300B systems are operational at customer sites. NXE:3300B is ASML's third generation of EUV systems and the first one delivered with MOPA + Pre-pulse EUV source technology. Deployment of Pre-Pulse technology enabled productivity capability of more than 600 wafers per day and further improvements in CO_2 drive laser performance, EUV source Conversion Efficiency and optical transmission are being deployed to further increase productivity performance. Overlay and Imaging performance in line with the requirements of 10 nm logic devices have been demonstrated and matched Machine overlay to ArF immersion below 3.5 nm and full wafer CDU performance of less than 1.5 nm are regularly achieved. Flexible pupil formation has been proven, while defectivity has been reduced in a year. The first full scale pellicles have been manufactured and demonstrated on an exposure tool as capable of preserving good imaging performance. I will present an overview of the current EUV performance and of the on-going developments also on the source development.

Presenting Author

Wim van der Zande is Director of Research at ASML since 2014. The themes of his research team encompass physics and chemistry processes in the LPP Source and the scanner, including material science for future pellicle materials and possible resist developments. Prior to 2014, he worked in academics at the Radboud University Nijmegen and the FOM Institute AMLF in Amsterdam.

S3

Laser Plasma Sources of Soft X-rays and Extreme ultraviolet (EUV) for Application in Technology and Science

Henryk Fiedorowicz

Institute of Optoelectronics, Military University of Technology, Warsaw, Poland

Laser plasma sources of soft x-rays and extreme ultraviolet (EUV) developed for application in various areas of technology and science are presented. The sources are based on a laser-irradiated gas puff target. The targets formed by pulsed injection of gas under high-pressure are irradiated with nanosecond laser pulses from commercial Nd:YAG lasers generating pulses with time duration from 1ns to 10ns and energies from 0.5J to 10J at 10Hz repetition rate. The gas puff targets are produced using a double valve system equipped with a special nozzle to form a double-stream gas puff target which secures high conversion efficiency without degradation of the nozzle. The use of a gas puff target instead of a solid target makes generation of laser plasmas emitting soft x-rays and EUV possible without target debris production. The sources are equipped with various optical systems, including grazing incidence axisymmetric ellipsoidal mirrors, a "lobster eye" type grazing incidence multi-foil mirror, and an ellipsoidal mirror with Mo/Si multilayer coating, to collect soft x-ray and EUV radiation and form the radiation beams. Application of these sources in various fields, including imaging in nanoscale, pulsed radiography and tomography, processing of materials and modification of polymer surfaces, photoionization of gases, and radiobiology is presented.

Presenting Author

Henryk Fiedorowicz received M.S. degree in technical physics in 1975, Ph.D. degree in material engineering in 1989, both from the Military University of Technology in Warsaw and habilitation in physics in 1998 from the Institute of Physics Polish Academy of Sciences in Warsaw. From 1975 to 1992 he worked at the Institute of Plasma Physics and Laser Microfusion in Warsaw and investigated laser-produced plasmas using X-ray diagnostics. In 1992 he joined the Institute of Optoelectronics at the Military University of Technology in Warsaw, where he established a laser-matter interaction laboratory. He has proposed a new method of generation of X-rays and extreme ultraviolet (EUV) from a laser-irradiated gas puff target. His recent works focus on the development, integration, and application of laser-plasma X-ray and EUV sources, including X-ray lasers. He was director of the Institute of Optoelectronics from 2002 to 2010 and a full professor from 2010. He is author of about 250 scientific publications.

S11

Research of the Tin Droplet Generator and Plume Expansion of Laser Produced Tin Droplet Plasma

Chen Ziqi, Wang Xinbing and Zuo Duluo

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A monitoring system has been developed to investigate the spatial stability of the tin droplets used for laser produced plasma EUV light sources. Two CCDs are set up at the orthogonal angle to detect the characteristics and stability of tin droplets. The motion and stability of the tin droplets can be displayed by image capturing and processing in real time. In our experiments, the tin droplets generated by a self-made tin generator present a suitable spatial stability for the synchronous laser irradiation. The droplet spacing is about 2.5 times of droplet diameter which is about 180 μ. And the lateral displacement of tin droplet is under 50% of the droplet diameter. The tin droplet of 20~40 kHz is irradiated by a 1~10 Hz Nd:YAG laser through the signal frequency division. Meanwhile, image sequences of plasma are acquired by an ICCD under different laser irradiances. The temporal evolution of plasma expansion demonstrates that the plasma shape develops from a circle to an ellipse, then to a flat ellipse. It is observed that the plasma expands faster in laser incoming direction than in laser orthogonal direction. And we found that the plasma centroid moves reverse the laser propagation direction during the expansion of plasma. The moving velocity of plasma centroid is estimated to be 6 km/s, which has no obvious relation with the laser intensity.

Acknowledgement: This research is supported by Director Fund of WNLO.

Presenting Author

Chen Ziqi is the presenting author for this annual workshop. He is a Ph.D candidate at Huazhong University of Science & Technology, Wuhan, China. He has started his doctorate of optical engineering at Laser and terahertz laboratory in Wuhan National Laboratory for Optoelectronics since 2012. His main research is laser produced tin-droplet plasma EUV source.

S12

Performance of One Hundred Watt Source and Construction of 250 Watt HVM LPP-EUV Source

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

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We have been developing CO_2-Sn-LPP EUV light source which is the most promising solution as the 13.5 nm high power light source for HVM EUVL. Unique and original technologies such as combination of pulsed CO_2 laser and Sn droplets, dual wavelength laser pulses shooting and mitigation with magnetic field have been developed in Gigaphoton Inc. 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 250 W EUV power will be able to realize around 20 kW level pulsed CO_2 laser. We have reported engineering data from our resent test such around 43 W average clean power, CE of 2.0%, with 100 kHz operation and other data [1)].

We have already finished preparation of higher average power CO_2 laser more than 20 kW at output power cooperate with Mitsubishi electric cooperation[2)]. Recently we achieved 140W with 50kHz, 50% duty cycle operation and 2 hours operation at one hundred watt power range[3)]. Recently we have demonstrated 24 hours operation at 80-50W level operation under power feedback. Further improvements are underway, we will report the latest challenge to more than one hundred watt stable operation, around 4% CE with 20 micron droplet and magnetic mitigation. Also I will report latest status and data of 250 W HVM LPP-EUV source construction.

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3) Hakaru Mizoguchi et al.:" Performance of one hundred watt HVM LPP-EUV Source " Proc. SPIE 9422 , (2015) [9422-11]

Presenting Author

Hakaru Mizoguchi is the Executive Vice President and CTO of Gigaphoton Inc.

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

S13

Studies of Laser-produced Tin plasmas for EUV Light Sources using Collective Thomson Scattering

Kentaro Tomita[1], Yuta Sato[1], Toshiaki Eguchi[1], Shoichi Tsukiyama[1], Kiichiro Uchino[1], Tatsuya Yanagida[2], Hiroaki Tomuro[2], Yasunori Wada[2], Masahito Kunishima[2], Takeshi Kodama[2], Hakaru Mizoguchi[2]

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Collective Thomson scattering (CTS) techniques have already been applied to a wide range of laser-produced plasmas. We have focused on developing a new CTS system for laser-produced extreme ultra-violet (EUV) light source plasmas. This plasma is an attractive candidate for EUV lithography at a wavelength of 13.5 nm. The plasma is expected to have a high electron density (n_e = 10^{24}–10^{25} m^{-3}) and a moderate electron temperature (T_e = 30–50 eV). The unique difficulty to measure such plasmas is a narrow width of the ion feature spectrum due to the moderate temperature and high stray light from the target materials.[1)] Moreover, plasma size is less than 0.5 mm and more than 0.1 mm spatial resolution is needed. In order to solve these problems and apply CTS, a special spectrometer has fabricated with more than 5 diffraction gratings. The spectrometer has an instrumental width less than 18 pm and a sufficient stray-light rejection at ±14 pm from the probing laser wavelength (532 nm). The plasma was produced with droplet tin having 26 μm diameter, and a structure of the plasma has been clarified as spatial profiles of n_e, T_e, averaged ionic charge, and drift velocity.

Reference

1) Kentaro Tomita et al.:"A Collective Laser Thomson Scattering System for Diagnostics of Laser-Produced Plasmas for Extreme Ultraviolet Light Sources", Appl. Phys. Express 6, 076101 (2013).

Presenting Author

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

S14

Research of CO_2 Laser Produced Sn and SnO_2 plasma

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The plasma plume expansion, ion debris and spectroscopic characterization of CO_2 laser produced Sn and SnO_2 plasmas have been investigated under identical experiment conditions by a CO_2 laser with a full width at half maximum of 80 ns. The expansion parameters of laser produced plasma(LPP) were estimated by means of a fast gated intensified charge coupled device (ICCD) imaging system, while the ion debris was detected using a Faraday cup with the time- of– flight (TOF) method. Meanwhile, the spectral emission of both plasmas have been investigated using a Princeton spectrograph. Furthermore, the extreme ultraviolet (EUV) emissions have been measured by a grazing incidence flat-field spectrograph. The ICCD images shows that Sn plasma plume has a hemispherical shape, while a cone shape plasma plume is observed in SnO_2 plasmas. Due to the difference on the thermodynamic parameters of samples, the total amount of ion number and the kinetic energy are both higher for SnO_2 plasma compared with Sn plasma. Optical emission spectroscopy (OES) obtained from SnO_2 target shows an obvious higher in the optical emission intensity than that of Sn target. The maximum estimated conversion efficiency (CE) of Sn and SnO_2 plasmas are 1.2% and 0.9%, respectively, due to the lower density of Sn in SnO_2.

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Presenting Author

Lan Hui is the presenting author for this annual workshop. She is a Ph.D candidate at Huazhong University of Science & Technology, Wuhan, China. She has started her doctorate of optical engineering at Laser and terahertz laboratory in Wuhan National Laboratory for Optoelectronics since 2011. Her main research is laser produced tin plasma EUV source.

S15

Droplet Generator for High Brightness LPP EUV Source

Alexander Vinokhodov[1], Vladimir Krivtsun[1,2], Mikhail Krivokorytov[1], Yury Sidelnikov[1,2], Viacheslav Medvedev[1,2], Konstantin Koshelev[1,2]

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The results of investigation of droplets generator, which are supposed to be used to generate a droplet target in high brightness LPP EUV source are presented. The size of the generated droplets from tin-indium alloy was varied in the range from 40 to 120 microns, the repetition rate from 20 to 120 kHz, velocity up to 10 m/s. For droplets with different diameters the spatial stability of the droplet mass center with sigma of less than 0.5 microns in the transverse direction to the droplets velocity vector and less than 1 micron in the longitudinal direction were obtained at distance of about 50 mm from the nozzle with annular piezoelectric actuator. A study of the droplets spatial stability at long time operation was carried out. At 50 kHz droplets repetition rate the droplets deformation was investigated under the influence of the LPP plasma nearby droplet at average pulse power of ~ 10^{11} W/cm^2 in a hydrogen atmosphere up to of 200 Pa.

Presenting Author

S16

Correlation between Laser Absorption Process and Energy Conversion to Extreme Ultraviolet Radiation in Laser Produced Tin Plasma

Hiraku Matsukuma[1],Atsushi Sunahara[2], Tatsuya Yanagida[3], Hiroaki Tomuro[3], Kouichiro Kouge[3], Takeshi Kodama[3], Tatsuya Hosoda[1], Shinsuke Fujioka[1], and Hiroaki Nishimura[1]

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The relatively low absorption of CO_2 laser is a crucial problem for efficient generation of EUV light source. In order to solve this problem and to increase the energy absorption, a double pulse method has been proposed where plasma scale length is extended by pre-pulse irradiation (S. Fujioka et al., Appl. Phys. Lett., 92, 241502 (2008).). It is important to measure the CO_2 laser absorption rate precisely in order to optimize plasma conditions. For this purpose we developed an integrating sphere for the CO_2 laser. The correlation between the laser absorption and CE for 13.5 nm EUV in a laser-produced tin plasma was investigated.

The absorption rate and CE were simultaneously measured for a laser-pre-formed low-density tin target as a function of the time delay between the pre-pulse and the main laser pulse. A clear positive correlation between absorption rate and CE was found with increasing delay time; however, CE decreases rapidly for longer delay times. This result is attributed partly to a decrease in the absorption rate, but is mainly attributed to self-absorption of EUV light in excessively long-scale plasmas.

Presenting Author

Hiraku Matsukuma was born in Japan in 1984. Currently he is a Postdoctoral fellow in the Institute of Laser Engineering, Osaka University. In 2013 he graduated from Graduate School of Engineering, Kyoto University with a Ph.D in Engineering.

S17

Hydrodynamics Modeling of the Dynamics of Sn droplet Target for the EUV Source

Akira Sasaki

Kansai Photon Science Institute, Japan Atomic Energy Agency, Kyoto, Japan

Improvement of the efficiency and output power of the EUV source is essential for the realization of the next generation micro-lithography. Recently, a high efficiency is obtained using the double pulse technique, where the Sn droplet is broken up into particles by the irradiation of the relatively weak pre-pulse laser. For the optimization of the source, we study methods for the modeling of pre-plasma formation including the solid/liquid to gas phase transition of Sn and particle emission. Firstly, we show a new Lagrangian hydrodynamics simulation using a dynamic mesh reorganization technique, which is used to model clusters and bubbles. Secondly, we show the equation of state of Sn for the simulation, which consists of the equation of state of ideal solid/liquid and gas. Thirdly, an algorithm to calculate distribution of solid/liquid and gas phase after the phase transition taking the conservation of the free energy. Finally, results of test calculation of the evaporation hot Sn droplet are discussed.

Presenting Author

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

S18

ARCNL's Laser-produced Plasma EUV Source

D. Kurilovich, F. Torretti, W. Ubachs, R.A. Hoekstra, O.O. Versolato

Advanced Research Center for Nanolithography, Science Park, Amsterdam

An extreme-ultraviolet (EUV) light source working at low rep-rate (10 Hz) was built and commissioned at ARCNL. It is based on a laser-produced plasma (LPP) generated by the irradiation of a high-energy pulse from a Nd:YAG laser at 1,064 nm onto tin droplets. We are currently setting plasma diagnostic tools including those for imaging and spectroscopy at EUV and visible wavelengths, as well as ion detectors and shadowgraphy cameras which enable high-speed "movies" to be obtained from exploding droplets.

Presenting Author

Dmitry Kurilovich is a Ph.D. student in the Advanced Research Centre for Nanolithography (ARCNL) in Amsterdam. His current research activities are focused on laser-droplet interactions and plasma diagnostics in an EUV light source based on a laser-produced tin plasma.

S19

A Study of Colliding Plasma Processes for Elements of Different Mass

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[2]*University of Paris-Sud, 15 Street Georges Clemenceau, 91400 Orsay, France*

Reheating of a Nd:Yag produced plasma with a CO2 laser pulse has been shown to increase the conversion efficiency of laser radiation into 13.5 nm radiation, which is relevant to source development for next generation lithography. One purposed plasma for reheating was a stagnation layer formed between two colliding laser produced plasmas [1]. Properties of the stagnation layer, such as time of formation, duration and shape evolution, can be controlled so that the coupling of the reheating pulse into the plasma is optimized.

In this work we study differences in stagnation layer evolution for three elements, Si, Sn and Pb, investigated with iCCD images of optical emission from the plasma. Knowledge of how the mass of the colliding plasma particles affects the formation and properties of the stagnation layer, may facilitate better coupling of the reheating laser pulse to the plasma.

References

[1] T. Cummins, C. O'Gorman, P. Dunne, E. Sokell, G. O'Sullivan, and P. Hayden. Colliding laser-produced plasmas as targets for laser-generated extreme ultraviolet sources. Applied Physics Letters, 105(4), 2014.

Presenting Author

Mr Domagoj Kos finished an integrated Bachelors and Masters degree in Physics in September 2013 and was awarded a Master of Science in Physics qualification by the Faculty of Science, University of Zagreb. His Masters thesis title was "Spectroscopic analysis of colliding laser produced plasmas" and the work was done under supervision of dr. sc. Nika Krstulovi in the Laboratory for Cold Plasma Laser Spectroscopy, Institute of Physics, Zagreb.
After his Masters degree, Mr Kos has spent one year working as an intern in the Institute of Physics, Zagreb, as well as working as a teaching assistant and demonstrator in the Department of Physics, Faculty of Science, University of Zagreb. In September 2014 Mr Kos has started the EXTATIC Erasmus Mundus Joined Doctorate Programme in UCD through which he moved to CTU in Prague in September 2015. He is continuing his research on colliding laser produced plasmas.

S20

Radiation Hydrodynamic Simulation of Laser-produced Tin Plasmas

A. Sunahara[1], H. Matsukuma[2], K. Nishihara[2], and A. Sasaki[3]

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In order to accurately simulate the scheme of achieving a 250 W output power extreme ultraviolet (EUV) light source for semiconductor lithography, we developed a multi-dimensional radiation hydrodynamic simulation code. In our double pulse scheme, the pre-pulse laser irradiates a tin droplet, and after some time delay, the main CO2 laser irradiates the expanding pre-formed plasma, emitting the EUV 13.5 nm 2% bandwidth light. The code improved the accuracy of simulating the physical model.

The plasma in this case has relatively large spatial and temporal evolution, which makes the simulation rather difficult. Our multi-dimensional radiation code enables us to accurately simulate this double pulse irradiation scheme. One of the merits is the radiation transport. We developed a M1 transport routine and combined it with our radiation hydrodynamic code. This code is able to treat the M1 radiation transport properly, including the anisotropic distribution of the radiation fields. The anisotropy becomes important for the temporal evolution of the tin droplet, if the droplet is on one-side is irradiated by the pre-pulse laser. Also, we improved our numerical accuracy, properly conserving the physical conserved values such as mass, momentum and energy. The code uses an improved equation of state of tin, since the liquid-gas mix phase is quite important in the dynamics of the tin droplet.

By using our code, we optimized the scheme of the laser-produced tin plasma for obtaining an efficient high power EUV emission. We will present the results of simulations, and benchmark by experimental tests. Further, we will discuss the possibility of obtaining higher power EUV Light sources beyond the 250 W output required in the EUV lithography.

Presenting Author

S21

Picosecond, kW Thin-disc Laser Technology for LPP and FEL EUV Sources

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[2)] *RISE, Waseda University, Tokyo, Japan*

Picosecond pre-pulse is one of the key technologies in the Sn droplet HVM LPP source for higher CE and full ionization by the main ns CO_2 laser pulse. Pulse energy of mJ level is available at 100 kHz from a compact thin disc laser regenerative amplifier. Shorter wavelength is preferable and an efficient and stable wavelength conversion is desired. EUV FEL is now under preliminary consideration in the industry for ultimate 40 kW operation. More advanced picosecond laser technology is necessary for photocathodes, laser e-beam heating, and HGHG seeding for the operational target. HiLase Centre is dedicated for the high average power, picosecond laser technology, which is best suited for these advanced applications. This paper reports on our recent research work on 100 kHz - MHz, picosecond UV laser technology.

Presenting Author

S22

Current Progress on Design Work of High Power EUV-FEL based on ERL

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High power EUV light source is strongly desired by a lithography society. A free electron laser (FEL) light source based on energy recovery linac (ERL) is one promising possibility to generate high power EUV light, such as more than 10 kW. Design work of EUV-FEL ERL is in progress. Our machine design is based on 10 mA and 800 MeV electron beam operation, in order to realize such intense EUV light. A high current CW electron gun, sophisticated handling of low emittance electron beam, generation of FEL light at undulators and stable operation of superconducting RF cavities are key technologies. Beam dynamics study has much progress including simulation about injector, bunch compression, decompression and interaction with undulators and optimized against efficient FEL generation. Superconducting cavity and cryomodule design are also optimized for the EUV sources. Current progress on above design work will be presented.

Presenting Author

Kensei Umemori graduated from the Graduate School of University of Tokyo in 2000. From 2000 to 2002 he worked at Hiroshima Synchrotron Radiation Center at Hiroshima University. Since 2002 he is working at High Energy Accelerator Research Organization (KEK).

S23

A Kilowatt Storage Ring EUV Source Based on Steady State Microbunching

Alexander Chao, Daniel Ratner

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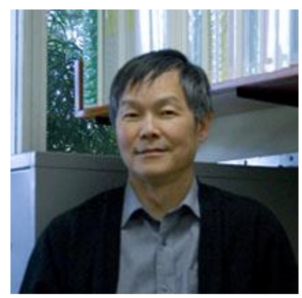
A recently proposed technique for storage rings is applied to provide potential high-power sources of photon radiation. The technique is based on the steady-state microbunching (SSMB) mechanism [1]. As an example of this application, one may consider a high-power kilowatt EUV radiation source for industrial lithography. The considered hardware includes a 1-GeV conventional room temperature electron storage ring equipped with a high power seed IR laser and three undulator magnets. While kilowatt tools will require a dedicated storage ring, a less challenging proof-of-principle test of the SSMB mechanism to produce IR radiation using an existing storage ring is also proposed.

[1] Daniel F. Ratner and Alexander W. Chao, Phys. Rev. Lett. 105, 154801 (2010).

Presenting Author



Alexander Chao is a professor at SLAC National Accelerator Laboratory, Stanford University. He received his Ph.D. at Stony Brook University in New York in 1974, and has worked at SLAC since then, except for a period of nine years when he was dedicated in vain to the project of Superconducting Super Collider, first in Berkeley and then in Texas. His recent interest has been brought to high power radiation sources using accelerator techniques.

S24

Experimental and theoretical studies of tin droplets shaping with picosecond laser pre-pulses

M. Krivokorytov[1], D. Kim[1,2], A. Vinokhodov[3], M. Basko[1,2], Yu. Sidelnikov[1,4], V. Medvedev[1,4], V. Krivtsun[1,4], and K. Koshelev[3,4]

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Shaping of droplet targets with laser pre-pulses is of great importance for laser-produced plasma sources of extreme ultraviolet radiation for lithographic applications. It was previously shown that picosecond pre-pulse technology provides target configuration resulting in record conversion efficiency values for EUV sources driven by CO_2 laser radiation [1]. However the a detailed description of the process of target deformation induced by the intense picosecond laser pre-pulses is lacking. In this talk we report on the experimental and theoretical studies of the target deformation by picosecond laser pulses. We applied high-speed stroboscopic imaging to characterize the dynamics of target deformation. The experiments are supported by radiative hydrodynamics simulation of laser-target interaction, which provides detailed picture of the studies physical process. Our simulations indicate that the observed target deformation dynamics results from the propagation of the laser-induced shock wave through the volume of initial droplet, which takes place during several tens nanoseconds after the laser pulse.

1. H. Mizoguchi et al., "Performance of one hundred watt HVM LPP EUV Source" Proc. SPIE 9422, Extreme Ultraviolet (EUV) Lithography VI, 94220C (March 13, 2015); doi: 10.1117/12.2086347

Presenting Author

S31

Bright and Reliable Xe-based EUV Source for Metrology and Inspection Applications

Oleg Khodykin

RAPID, KLA-Tencor Inc.

Extreme ultraviolet lithography (EUVL) is the leading patterning technology beyond 193 nm immersion lithography. With Cymer/ASML’s EUV source having achieved 80 W EUV power level and customers starting to process over 1000 wafers in 24 hours, EUVL, while still in development, continues to be on the roadmaps of leading semiconductor chip makers to extend Moore’s law below the 10nm node.

Availability of defect-free EUV lithographic masks is considered to be one of the major challenges for the future of EUVL. Since current optical inspectors are expected to catch critical defects on EUV masks down to about 20 nm half pitch (~10 nm node) and e-beam inspectors suffer from low throughput and are incapable of inspecting through a protective pellicle, an actinic mask inspector at 13.5 nm is believed to be necessary. EUV program in the RAPID division is focused on the development of an actinic patterned mask inspection tool to support the EUVL roadmap. Similar to lithography, one of the major challenges facing the program is the development of a clean and bright 13.5 nm EUV light source for mask illumination. However, requirements for the inspection source are different from those for lithography. While lithography demands high EUV light source power to achieve economical throughput, for mask inspection the critical parameter is brightness measured in W/(mm^{2}sr), which depends not only on the power but also on the size of the source emission volume.

In this presentation we will discuss progress toward stable long-term operation of the Xenon drum-based laser produced plasma (LPP) EUV light source at the brightness level required for the 1st generation of EUV mask inspection tools. Implemented debris mitigation techniques resulted in no EUV reflectivity degradation for a proxy-collector within 0.5% measurements accuracy, which represents over >100x improvement of the collector lifetime over the last year. The source performance exceeds that of any other EUV source for metrology or inspection available in the industry. Recent progress also compares very favorably to the current state of the EUV sources for lithography. Plans for further improvements of EUV source are discussed.

Presenting Author

Oleg Khodykin is a Manager of EUV development in KLA-Tencor's RAPID division in Milpitas, California. Prior joining KLA-Tencor in 2011, he worked at CYMER for 10 year as senior scientist and EUV collector group leader on different concepts of EUV source (both discharge and LPP, lithium, xenon and Sn based). Dr. Khodykin received his Ph.D. from Moscow Physical-Technical Institute in 1998 and did postdoctoral training at Bayreuth University and at the University of Southern California.

S32

Discharge based EUV Source for Metrology and Inspection

Klaus Bergmann, Alexander von Wezyk and Jochen Vieker

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Discharge based EUV sources offer a compact and cost effective alternative for metrology and inspection applications. Such sources are commercially available and being used in the environment of EUV lithography development, e.g., mirror contamination studies, mask blank inspection or resist development.

We report on our latest results of the FS5420 source generation, which is under development at Fraunhofer ILT. The concept is based on a hollow cathode triggered Xenon pinch plasma (HCT). The standard in-band emission power level at 13.5 nm is 20 W/(2πsr 2% b.w.) at a typical repetition rate in the range of 1-2 kHz. Progress on long-term stability and power scaling to more than 40 W/(2πsr 2% b.w.) will be presented. Major improvements on long term stability are based on new electrode materials showing less electrode erosion, as well as the development of an improved triggering concept reducing the influence of electrode erosion on the source performance. An outlook on the potential for 6.x nm will be given.

Presenting Author

Klaus Bergmann was born in Dinslaken, Germany in 1966. He received the M.S. degree in physics and Ph.D degree from the University of Technology, Aachen, Germany, in 1992 and 1996, respectively. Since 1992, he has been with the Department for Plasma Technology, Fraunhofer Institute for Laser Technology. He was occupied with the investigation of plasma focus devices as radiation sources in the soft X-ray range and pseudospark switches for applications for high pulsed currents. Currently, he is Group Leader for the development of radiation sources for use in future semiconductor lithography. The focus of work is the scaling of gas discharge based EUV-sources and their application in structuring and analysis.

S33

Combination of Discharge and Laser-produced Plasmas for High Brightness Extreme ultraviolet (EUV) Light Sources

Florian Melsheimer[1,2,3]; Richard Lensing[1,2,3], Girum Beyene[1,2,3,4], Xiaoduo Wang[1,2,5], Larissa Juschkin[1,2,3]

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[5]Changchun Institute of Optics, Fine Mechanics and Physiks, University of Chinese Academy of Sciences)

We present the concept of a compact EUV light source using a hybrid approach combining the techniques of discharge and laser produced plasmas. In this so called laser-heated discharge plasma (LHDP) approach a Z-pinch plasma is electrically generated and optically heated. The goal of the project is to generate highly brilliant incoherent EUV radiation with minimum required laser pulse energy and discharge currents. To achieve this, the discharge of a triggered hollow cathode source produces and confines a ”cold” and dense plasma, which is used as a target for a pulsed Nd:YAG laser beam. The optical heating of the plasma partially restores the energy, which is lost due to the EUV emission. Thus the time for the emission of EUV radiation is prolonged and the collapse due to energy losses can be delayed. Furthermore the etendue of the EUV emission is reduced, since the size of the optically heated area is controlled by the laser focus diameter, which is far smaller than the Z-pinch diameter.

Presenting Author

Since 2013 Florian Melsheimer is working on his Master of Science at Rheinisch Westfälisch Technische Hocheschule, Aachen, in the field of Nanoelectronics. His master’s thesis is titled “Coupling of a laser beam into gas discharge plasma for increased brilliance of the extreme ultraviolet light emission.” He received the Bachelor of Science from Rheinisch Westfälisch Technische Hocheschule, Aachen with thesis titled “Investigation of Alq_3 film growth – Impact of different circumstances on growth and morphology of Alq_3 layers.

S34

Experimentally Validated Neutral Cluster Debris Mean Velocity and Trajectory Model for Droplet-Based Laser Produced Plasma Sources

Duane Hudgins, Nadia Gambino, Bob Rollinger and Reza S. Abhari

Laboratory for Energy Conversion, Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland
Adlyte AG, Zug, Switzerland

In a droplet-based EUV laser-produced plasma source the tin debris velocity and trajectory were measured as a function of laser pulse irradiance. An analytical model is derived, which describes the neutral cluster debris velocity and trajectory using conservation of energy and momentum. The fuel droplet and subsequent debris breakup has been imaged for different Nd:YAG, 1064 nm pulsed laser irradiances ranging from 5-150 GW/cm^2 with a high-speed shadowgraph imaging system. For the different laser irradiances, the debris velocity and trajectory are measured on the parallel plane to the laser axis using in-house image analysis software. The model is validated against the analytical results are in good agreement with the measurements. The dominant mechanism for transferring momentum to the neutral cluster debris is the ablation pressure acting on the unablated droplet volume. A relation that describes the neutral cluster debris deflection as a function the laser spot size, is also derived and experimentally validated.

Presenting Author

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

S35

High-radiance LDP Source: Clean, Reliable and Stable EUV Source for Mask Inspection

Yusuke Teramoto, Bárbara Santos, Guido Mertens, Ralf Kops, Margarete Kops, Hironobu Yabuta, Akihisa Nagano, Noritaka Ashizawa, Takahiro Shirai, Kunihiko Kasama, Alexander von Wezyk[1] and Klaus Bergmann[1]

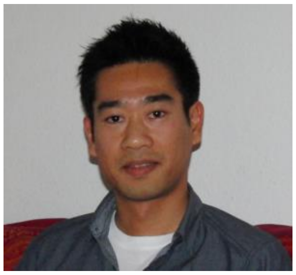
USHIO Inc.

[1]Fraunhofer ILT

High-throughput actinic mask inspection tools are needed as EUVL begins to enter into volume production phase. One of the key technologies to realize such inspection tools is a high-radiance EUV source of which radiance is supposed to be as high as 100 W/mm^2/sr. Ushio is developing laser-assisted discharge-produced plasma (LDP) sources. Ushio's LDP source is able to provide sufficient radiance as well as cleanliness, stability and reliability. Radiance behind the debris mitigation system was confirmed to be 120 W/mm^2/sr at 9 kHz and peak radiance at the plasma can be as high as 180 W/mm^2/sr. One of the unique features of Ushio's LDP source is cleanliness despite liquid tin as fuel material. Source cleanliness was evaluated by placing a Ru mirror sample behind the debris shield. Multiple samples were exposed for at least 100 Mpulse and surface of each sample was analyzed with XRF and SEM. Deposition of tin was negligible and sputter rate of ruthenium was a few nm per Gpulse. Collector lifetime is therefore considered to be sufficiently long. Days-long, non-interrupted runs were also carried out to address system reliability and long-term stability. A prototype machine has been built and tested for product development.

Presenting Author

Yusuke Teramoto received his Ph.D. degree in 2002 from Kumamoto University, Japan. He joined Ushio Inc. in April 2002 and started research and development on Xe and Sn fueled discharge EUV source. In 2008, he moved to Aachen, Germany to participate the co-development program between Ushio, XTREME, Philips and Fraunhofer ILT. He engaged in source development for NXE3100, especially in power scaling. Now he is a senior project manager and in charge of Germany unit to conduct marketing and development of EUV source for mask inspection and non-litho applications.



S36

Tin Droplets for EUV Sources

Alexander Sanders, Bob Rollinger, Nadia Gambino, Duane Hudgins, Markus Brandstätter, Marco Weber and Reza S. Abhari

Laboratory for Energy Conversion
Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland

The major challenges of current metrology EUV sources – the pulse-to-pulse stability, the limited output power as well as the generation of debris are all directly related to the droplet target characteristics. In this work, the droplet characteristics such as drop-to-drop stability as well as droplet size are assessed experimentally. Further, they are characterized as function of key operating parameters of the droplet generator, such as excitation strength, frequency and backpressure.

In the second part of this work, the dependence of the EUV pulse energy on the droplet diameter is shown. The droplet size determines the size of the EUV emitting plasma and thus impacts directly the EUV pulse energy. However, in order to reduce neutral debris it is desired to use smaller droplets. Understanding the dependence of EUV energy on droplet diameter is thus crucial for optimizing the trade-off between EUV energy and neutral debris load. Due to droplet break-up considerations smaller droplets also result in a smaller separation distance between droplets. This can result in the irradiation as well as a disturbance of the droplet subsequent to the one irradiated at the laser focus. These trade-offs are also discussed and form a third part of this work.

Presenting Author

Alexander Sanders is a PhD student supervised by Prof. Reza Abhari in the Lab for Energy Conversion at ETH Zurich. He is working in the field of EUV Sources based on Laser-produced Plasma. His research interests include droplet formation and how various droplet characteristics affect the performance of LPP light sources.Alexander received a Master degree in Engineering, Economics and Management from the University of Oxford in 2013.

S37

Light Sources for High Volume Metrology and Inspection Applications

Reza S. Abhari

ETH Zurich, Switzerland

Recent progress on source cleanliness with a focus on three layers of debris mitigation strategy will be provided, together with the impact on operating time, availability and cost-of-ownership. Update on the main focus of development, namely 24/7 operation, has shown significant progress in demonstrating source stability, brightness as well as cleanliness requirements for high volume manufacturing needs for all actinic mask inspection needs, such as pattern inspection, AIMS, as well as mask blank.

The latest research achievements program, which includes fast imaging of the EUV plasma and debris, will be presented showing the effectiveness of the debris mitigation system. In a recent effort, the emission wavelength window has been tuned for applications seeking sub-200 nm emission, such as wafer inspection. The continuous increase in technology readiness enables Adlyte, while working hand-in-band with industry leaders, to move towards productization of the light source. Prototype EUV sources for actinic mask inspection have been designed, developed, built and tested over the last 8 years. The targets of the laser-produced plasma light source are liquid metal micrometer droplets that are irradiated by a Nd:YAG laser with up to 1.6 kW of output power. A source brightness of 350 W/mm2sr has been reached. The pulse-to-pulse stability equals to 3% over long-term operation has been demonstrated. The source is operated with either normal or grazing incidence optics, depending on the inspection application.

Presenting Author

S38

Light Source Development at Energetiq Technology

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Energetiq Technology Inc.
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Energetiq Technology Inc. produces a variety of light sources. This poster will review the physics of these products (and some proposed devices), with an emphasis on applications. The technology to be described includes the basic EQ-10 at 13 nm wavelength, and related devices including higher power, high pulse rate, and proposed high brightness concepts, and the 2.88 nm source for water window microscopy derived from the EQ-10. In addition, we will present a summary of the physics and applications of the family of products based on Energetiq's Laser Driven Light Source technology.

Presenting Author

S41

The Advanced Research Center for Nanolithography

Joost W.M. Frenken

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Lithography is at the heart of the continued miniaturization of the basic components of memory and processor chips. EUV lithography is providing this development with a tremendous push. New, fundamental research is becoming increasingly important to enable further strides in this field. The Advanced Research Center for Nanolithography is a new public-private partnership between the Dutch funding agency FOM (Foundation for Fundamental Research on Matter), the University of Amsterdam (UvA), the VU University Amsterdam, and the semiconductor equipment manufacturer ASML. ARCNL focuses on the fundamental physics behind current and future technologies for application in nanolithography, in particular for the semiconductor industry.

In this talk, I will sketch the contours of ARCNL's research program and provide an example from the work of my own research group at ARCNL on atomic-scale surface processes. In particular, I will demonstrate how we employ scanning tunneling microscopy to acquire *live* movies of the deposition of molybdenum and silicon for the production of MoSi multilayer coatings for EUV optics. The STM-observations reveal the atomistic mechanisms at play and thus enable us to understand what limits the quality of the multilayers that are formed in these processes.

Presenting Author

Prof. dr. Joost W.M. Frenken is the Director of Advanced Research Center for Nanolithography (ARCNL) in Amsterdam, the Netherlands.

S42

Studies of Thermal Transport in Mo/Si Multilayer Structures

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The rapid development of high power extreme ultraviolet and soft x-ray radiation sources creates new challenges for optics related to the radiation induced damage. While significant efforts were previously spent on studying the radiation-induced structural changes in multilayer optics, much less attention has been given to the studies of mechanisms of heat transport in these structures. In this talk we present the studies of heat conduction phenomena in periodic Mo/Si multilayer structures with individual layer thicknesses below 10 nm. Such film thickness scale is smaller than the typical mean free path values of heat carriers in bulk materials, which results in strong anisotropy of heat conduction in-plane and cross-plane in multilayer structures. We discuss experimental techniques applicable for the characterization of thermal properties of such structures and demonstrate the measurements of thermal conductivity tensor for Mo/Si multilayer structures using the frequency-domain thermoreflectance. The results of the measurements are discussed together with the mechanisms of heat transport in multilayered nanostructures.

Presenting Author

S43

EUV and Beyond EUV Optics Research at the University of Twente

Eric Louis, Robbert van de Kruijs, Andrey Yakshin, Johan Reinink, Dmitry Kuznetsov, Ben Wylie van Eerd, Chris Lee and Fred Bijkerk, [1]Hartmut Enkisch and [1]Stephan Müllender

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Both 13.5 nm lithography (EUVL) and it's possible successor, 6.x nm lithography (Beyond-EUVL or B-EUVL) require the best possible multilayer performance in terms of reflectance, stability, radiation hardness, stress, bandwidth, etcetera. Within our Focus Group XUV Optics we carry out research on these aspects as well as on surface related topics.

In this presentation we will discuss the status of both EUV and B-EUV optics including the latest results. Special attention will be given to a new development, namely adaptive optics for the EUV and soft X-ray wavelength range.

Presenting Author

Eric Louis carried out research and development of EUV and soft X-ray multilayer reflective coatings since 1992. Initially at the FOM-Institute for Plasma Physics Rijnhuizen, later DIFFER and since 2014 in the Industrial Focus Group XUV Optics of the MESA+ Institute of the University of Twente in Enschede, the Netherlands.

He worked on multilayers for several applications such as space research and synchrotron applications, but focused his research primarily on EUV and beyond-EUV multilayers for lithography.Eric Louis has been responsible for research, development and the coating of several optics for the first EUV lithography tools now operational in semiconductor industry.
Furthermore he worked on layer smoothing mechanisms, stress mitigation, suppression of out of band radiation, lifetime issues and damage mechanisms when multilayers are exposed to extremely high photon fluxes.

S51

Feature of Unresolved Transition Array Emission in Water Window Soft X-ray Spectral Region from a Dual-pulse Laser-produced Bismuth Plasma

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We proposed the use of highly charged ions of Bi plasma as a laboratory scale water window soft x-ray source (λ = 2.3 – 4.4 nm) for a compact microscope with a single-shot flash imaging capability. We characterize the feature of unresolved transition array (UTA) emission in water window spectral region from a dual-pulse laser-produced bismuth plasma. The UTA emission in the water window soft x-ray spectral region mainly dominated by 4*d* – 4*f* and 4*f* – 5*g* transitions is strongly enhanced. The optimum separation time between the pre- and main pulses is observed to be around 10 ns. The corresponded total power emitted increases 1.2 times, while the source size is slightly smaller than that of the single pulse duration.

Presenting Author

Hiroyuki Hara is a master course student in engineering at the Utsunomiya University. His research activities have focused on hydrodynamic simulation with the atomic process in the plasmas for short-wavelength light sources.

S52

Laser-produced Multiply Charged Ion Plasma Sources for a Compact Water Window Soft X-ray Microscope

Yoshiki Kondo[1], Thanh-Hung Dinh[1], Goki Arai[1], Takeo Eijima[2], and Takeshi Higashiguchi[1]

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[2] Institute of Multidisciplinary Research for Advanced Materials (IMRAM), Tohoku University, 2-1-1, Katahira, Aoba-ku, Sendai, 980-8577 JAPAN

Imaging in the water window soft x-ray (SXR) spectral region (λ=2.3–4.4 nm) that benefits from the natural contrast between carbon and oxygen absorption is of great interest for the investigation of unstained biological samples. In this study, we focus on the multiply charged ion plasma sources for the use in a table-top microscope with a single-shot flash imaging capability. A SXR contact microscope has been developed in order to evaluate performance of the light sources. We also succeeded in single-shot flash imaging of mouse liver cell staining with haematoxylin, as a preliminary result.

Presenting Author

Yoshiki Kondo is a master course student in Utsunomiya University. His research activities have focused on developing compact micro-imaging systems in the water window soft X-ray spectral region.

S53

Absorption Spectral Structure in Highly-charged Zirconium Plasmas in Water window Soft X-ray Spectral Region

Takanori Miyazaki[1,2], Goki Arai[2], Hiroyuki Hara[2], Thanh-Hung Dinh[2], Takeshi Higashiguchi[2], Akinobu Irie[2],
Chihiro Suzuki[3], Daiji Kato[3], Akira Sasaki[4], Padraig Dunne[1], and Gerry O'Sullivan[1]

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[2]Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), Utsunomiya University, Utsunomiya, Tochigi 321-8585 Japan
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We have investigated the absorption spectral structure of laser-produced highly charged zirconium plasmas in the water window soft x-ray spectral region. We characterize the effects of self-absorption with the dual laser pulse irradiation method. Emission around 2−3 nm is strongly enhanced. Structure due to absorption, which originates from opacity effects in the recombination phase, was observed at a pulse separation time of around 100 ns.

Presenting Author

Takanori Miyazaki is a Ph.D. student in engineering at the Utsunomiya University, and a visiting student in the School of Physics at University College Dublin. His research activities have focused on atomic processes in high-*Z* plasmas and high brightness light source for a compact soft x-ray microscopy.

S54

Effects of Optical Thickness on Soft X-ray Spectral Feature Observed in Gd and Tb Plasmas

Chihiro Suzuki[1], Takeshi Higashiguchi[2], Atsushi Sasanuma[2], Goki Arai[2], Yusuke Fujii[2], Thanh Ding Hung[2], Fumihiro Koike[3], Izumi Murakami[1], Naoki Tamura[1], Shigeru Sudo[4]

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Soft X-ray emissions from gadolinium (Gd) and terbium (Tb) plasmas have recently been investigated as candidates for BEUV (beyond extreme ultraviolet) light sources around 6.x nm. In this study, soft X-ray spectra from Gd and Tb ions in CO2 laser-produced plasmas are compared with those in optically thick Nd:YAG laser-produced plasmas. These spectra are compared also with those in low-density optically thin plasmas produced in the Large Helical Device (LHD). Broadband UTA (unresolved transition array) emissions without any outstanding sharp peaks are observed in the spectra from Nd:YAG laser-produced plasmas. In contrast, the spectra from CO2 laser-produced plasmas comprise narrower UTAs with some discrete feature, the highest peak of which is due to a Pd-like resonance line. This trend is further enhanced in the LHD plasmas, which leads to higher spectral purity. A comparative study among these spectra observed under different optical thicknesses is presented with the help of atomic structure 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.

S55

Laser-Produced Plasma Spectroscopy of Medium to High-Z Elements in the 2 to 9-nm Spectral Region

Elaine Long[1], Chihiro Suzuki[2], John Sheil[3], Elgiva White[3], Ragava Lokasani[1], Bowen Li[1], Paul Sheridan[1], Patrick Hayden[4], Emma Sokell[1], Padraig Dunne[1], Fergal O'Reilly[1] & Gerry O'Sullivan[1]

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[3] Summer Intern at UCD School of Physics
[4] National Centre for Plasma Science & Technology and School of Physical Sciences, Dublin City, Dublin, Ireland

Much effort has gone into the development of plasmas as sources of radiation in the 2 to 9-nm region with particular interest in the "water window" region (2.3 to 4.4 nm) and at 6.X-nm [1,2]. Plasmas were formed on a range of targets of medium to high atomic number (Z) elements using Nd:YAG lasers. Spectra were recorded using a 0.25-m grazing-incidence spectrograph and spectral analysis was carried out with the aid of Hartree-Fock with configuration interaction calculations using the Cowan suite of codes [3].

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Presenting Author

S56

Experimental Study of the Interaction of Sub-nanosecond and Nanosecond Duration Laser Pulses with Solid Targets at Different Laser Energies

Ragava Lokasani[1, 2], Elaine Long[2], Oisin Maguire[2], Domagoj Kos[2], Paul Sheridan[2], Patrick Hayden[2], Fergal O'Reilly[2], Padraig Dunne[2], Emma Sokell[2], Akira Endo[3], Jiri Limpouch[1] and Gerry O'Sullivan[2]

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[2]UCD School of Physics, University College Dublin, Belfield, Dublin 4, Ireland.
[3]Institute of Physics of Academy of Sciences of the Czech Republic, HiLase Center, Za Radnici 828, 252 4, Dolni Brezany, Czech Republic

XUV emission is produced when high intensity pulsed laser irradiate solid targets. The emitted XUV radiation can be suitable for different applications that include nanolithography and biological imaging. XUV emission from slab targets of the elements from yttrium (Z=39) to palladium (Z=46) irradiated by Nd:YAG laser pulses with durations of 170ps and 7ns respectively were investigated systematically. The XUV emission was recorded with flat field grazing incidence spectrometer equipped with a variable groove spaced grating. The atomic structure code developed by Cowan[1] was used to generate simulated spectra for comparison with experimental results and enabled the identification of a number of new features arising from 3d-4p, 3d-4f and 3p-3d transitions. With increasing Z, transitions along particular isoelectronic sequences shift systematically to shorter wavelength so that while the spectra appear quite similar there is a gradual shift towards higher energy in going from yttrium to palladium. The major effect of laser pulse duration is to alter the ratio of 3d-4p, 3d-4p, and 3p-3d emission which is observed to be greater in the case of sub-nanosecond irradiation.

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Acknowledgments
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Presenting Author

S57

Colliding Laser - produced Plasma Experiments on Carbon Group Elements

O. Maguire[1], D. Kos[1], P. Oudayer[2], P. Dunne[1], F. O'Reilly[1], T. McCormack[1] and E. Sokell[1]

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[2]University of Paris-Sud, Orsay, France

The study of the behavior of Sn plasmas produced by laser ablation has been relevant to source development for lithography at 13.5 nm [1]. The work presented here is primarily concerned with the difference in plasma velocities for laser produced plasmas of group 4 elements from carbon to lead, with emphasis on silicon (low Z), tin (medium Z), and lead (high Z) plasmas. The velocities of the plasma have been extracted from CCD images obtained using a 250 ps gated ICCD Hamamatsu camera (C1764-03). This data has also been compared to ion velocity data, obtained from measurements made with two copper probes and an electrostatic energy analyzer (ESA). EUV spectra, from 9.8 to 18 nm, were recorded on an absolutely calibrated JENOPTIK EUV Spectrograph, and these spectra provide additional information about the temperature of the plasma. The emission spectra have been analyzed with the aid of the well known Cowan suite of atomic structure codes [2] [3] [4]. For a known plasma temperature the CR model predicts the ratio's of the relevant ion stages within the plasma [5]. The combination of all of this information about the plasmas will provide insight into the differing behaviors of the low, medium and high-Z plasmas.

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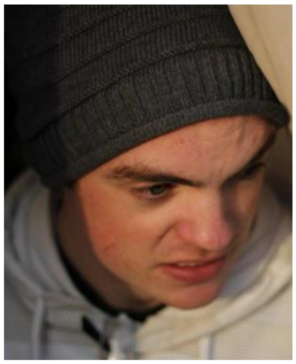
Presenting Author

Oisin Maguire a PhD student in the Spectroscopy (Spec) group at University College Dublin, my research is in the area of colliding laser produced plasmas.



S58

Identification of Plasma Sources for Water Window Imaging: Recent Spectroscopic Studies

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As is well known, the choice of wavelength for EUV lithography at 13.5 nm is based on the availability of Mo/Si multilayer mirrors (MLMs) with a reflectivity of ~70% at this wavelength. The optimum source has been identified as a laser produced Sn plasma, as lines from transitions of the type $4p^64d^n$ -$4p^54d^{n+1}$ + $4p^64d^{n-1}4f$ overlap in Sn^{10+} to Sn^{13+} to form an unresolved transition array (UTA) peaking at 13.5 nm [1]. Sources for other applications are being developed. Conventional sources for soft x-ray microscopy use line emission from liquid nitrogen or carbon containing liquid jets. Recently the possibility of using MLMs with $4p^64d^n$ -$4p^54d^{n+1}$ + $4p^64d^{n-1}4f$ UTA emission from highly charged Bi plasmas was proposed [2] and subsequently the possibility of using Δn=1 transitions in 2nd row transition elements was identified [3]. We have since studied the emission from laser produced plasmas of elements with Z>38 and succeeded in identifying a number of potential candidates based on 3d-4f arrays in the 2nd transition row elements and 4d-5f and 4f-5g arrays in elements with Z>70 [4]. These studies seek to identify spectral features that coincide with the reflectance characteristics of available MLMs with reflectance peaks lying in the water window and to determine the conditions under which they are optimized.

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Presenting Author

S59

Efficient EUV Sources by Short CO_2 Laser-produced Plasmas

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We develop the hybrid laser system with the sub-nanosecond laser and TEA CO_2 laser amplifier to produce the 3−15 ns short pulse and high energy pulses at a wavelength of 10.6 µm. We will report the preliminary experimental results of the extreme ultraviolet sources from the short CO2 laser-produced plasmas (LPPs).

Presenting Author

Atsushi Sasanuma is a graduate student in Utsunomiya University. His research activities have focused on short pulse, high energy CO2 laser system for efficient EUV and soft x-ray sources.

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Laboratory-based Photoemission Spectro-microscopy at 71.7 eV for Studies of Complex Materials

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This contribution is about the combination of a state of the art PEEM with an intense yet compact gas discharge light source to exploit the full strength of the state of the art photoemission microscope. We selected 71.7 eV (17.28 nm) and 113.7 eV (10.9 nm) photon energies for photoelectron imaging in the direct- and k-space to map the band structure of an Au (111) single crystal surface using the NanoESCA. To study the surface oxidation on islands of the phase-change material GexSbyTez grown in hexagonal crystal structure, we performed highly surface-sensitive spectro-microscopy with a laboratory-based light source previously only feasible at synchrotron beamlines and compare our results to ordinary XPS measurements with 1.486 keV photon energy.

Presenting Author

Currently Daniel Wilson is a PhD student in RWTH Aachen. The title of his PhD thesis is "Optimization of a compact plasma gas-discharge source with optics to select and focus spectral lines in the EUV for photoemission-spectroscopy and microscopy." He received Master of Science Physik from RWTH Aachen Aachen with a major in solid-state physics and thesis title, "Generation of Circularly Polarized Light in the Extreme Ultraviolet (EUV) for Element-Selective Magneto-Optics."

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X-ray Generation Enhancement from a Nano-structured Targets Irradiated by Long Laser Pulses

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Nanostructure targets are very attractive for enhancing the intensity of X-rays pulses generated from laser produced plasma and also as highly absorbing targets for high peak power sub-picosecond laser matter interaction. The influence of initial density of close-packed polystyrene microspheres, silicon wafer with-Sn and porous alumina targets covered by a thin tin layer has been quantitatively investigated for efficient extreme ultraviolet light emission source from laser produced plasmas. Targets were irradiated by 7 ns, 170 ps and 30 ps Nd:YAG lasers and spectra were recorded with a flat field grazing incidence spectrometer equipped with a variable groove spaced grating. We have investigated the variations of the emission spectra with the laser irradiance and with various pulse durations as well.

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Presenting Author

Ellie Floyd Barte is a doctoral candidate from Czech Technical University in Prague (CTU), Czech Republic. He received his MSc. Degree in Applied Physics Major in Medical Physics from the University of Santo Tomas, Manila, Philippines. Before joining CTU, he worked at St. Luke's Medical Center – Global City, Philippines as a medical physicist in the Radiation Oncology Department. He was involved in various quality assurance programs for their facility. Ellie joined EXTATIC Erasmus Mundus Joint Doctorate program in September 2014. His project title is "Using microstructures for laser-induced x-ray source enhancement from plasma produced by femtosecond and nanosecond lasers".

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Water-Window Microscope Based on Nitrogen Plasma Capillary Discharge Source

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We present a design of transmission water-window microscope based on nitrogen plasma generated by the Z-pinching capillary discharge source (table-top), operating at the wavelength λ = 2.88 nm. Plasma is generated by a current discharge through a 10 cm long, 3.2 mm inner diameter ceramic capillary filled with nitrogen gas. Average photons flux is 5 x 10^{13} photons/(sr x line x pulse), beam divergence is 30 mrad and source size is 360 µm. Soft X-ray radiation is filtered by Titanium filter (0.5 µm) and focused by an ellipsoidal (nickel coated) condenser mirror. The image of a sample is taken using a Fresnel zone plate onto a CCD camera. We demonstrate an image of a copper grid mesh with the magnification 300x, exposure time 1 min and the spatial resolution 110 nm (half-pitch).

Presenting Author

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

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Application of Lens-less Imaging Techniques for Nano-scale Microscopy Employing Plasma-based EUV Source

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The success of modern nano-science and nano-technology is greatly benefited from the development of new methods of high-resolution metrology. A subject of this lecture is a demonstration of new laboratory-based EUV and soft X-ray imaging methods. Illumination by short-wavelength light in the spectral region between 1 nm and 50 nm is highly advantageous for achieving high resolution and elemental contrast at the same time. The former is due to highly reduced diffraction limit, and the latter is because absorption edges of many common elements are located within the mentioned spectral range. This lecture is focused on application of lens-less coherent diffractive imaging (CDI) techniques including also scanning probe (ptychographic) CDI for phase-sensitive EUV microscopy with only partially coherent gas-discharge light source. The core of these techniques is in analyses of diffraction patterns produced when sufficiently coherent short-wavelength radiation illuminates a nano-structured sample. Results of experiments demonstrating CDI using compact high-radiance plasma sources developed for EUV lithography applications are presented. A silicon nitride sample structured by focused-ion-beam technique is imaged being illuminated by intense radiation of OVI emission line (17.3 nm wavelength). To account for only partial spatial coherence and for background from other wavelengths emitted by the plasma source, a novel linear correction method with a dynamical adapting deblurring kernel is implemented during the sample structure reconstruction. Image resolution of 150 – 250 nm has been achieved. The resolution is limited presently by the sample structure contrast and exposure time. This modified modulus constraint method, in combination with the narrow bandwidth of the plasma emission line, allowed spectral filtering by a single multilayer mirror without additional transmission filters. Our results show that compact plasma-based EUV light sources of only partial coherence not considered so far for coherent imaging can be effectively used for lens-less imaging applications. Steps to push the resolution towards the diffraction limit will be presented and application of multiple wavelengths CDI will be addressed.

Presenting Author

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ABSORPTION OF EUV RADIATION IN MATTER AND RELATED PROCESSES

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Investigation of short-wavelength ablation mechanism of PMMA, poly (1-hexadecene-sulfone) and PPEES, poly (1,4-phenylene ether ether-sulfune) is presented. Measurements on PMMA and PPEES have been done by EUV radiation at 13.5 nm using a table-top laser produced plasma from a gas-puff target at LLG, in Göttingen and at 46.9 nm by a 10 Hz desktop capillary-discharge EUV laser at the Institute of Physics, in Prague.

Ablation tests on PPEES were not successful at 13.5 nm. This can be explained considering that at 46.9 nm the ablation threshold should be much lower than at 13.5 nm and that during the exposure at 13.5 nm the near surface region is not so "overexposed/overheated" as at 46.9 nm. Analysis of ablation process limit based on comparison with the data obtained by the 10.8nm / 0.8 J / 3ns EUV source at the Institute of Optoelectronics (IOE) at the Military University of Technology in Warsaw is presented. During a second experimental campaign PPEES and PHDS have been irradiated in Prague and Warsaw and the results have been compared. Both systems provided ablation results because of long wavelength (Prague) and non-monochromaticity (Warsaw). The limits of the ablation process, with particular focus on the optical elements effect, are discussed.

Presenting Author

Chiara Liberatore is a PostDoc at the Institut national de la recherche scientifique (Energy, Materials and Telecommunications Research Centre), in Québec, Canada. She received PhD from Czech Technical University in Prague. During her PhD she also worked as a junior Researcher at Hilase Centre in Prague.

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