2014 International Workshop on EUV and Soft X-Ray Sources

November 3-6, 2014

Dublin ▪ Ireland

Workshop Abstracts

EUV Litho, Inc.

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2014 International Workshop on EUV and Soft X-ray Sources

Workshop Sponsors

Workshop Co-Organizers

Welcome

Dear Colleagues;

We are ready to welcome you to the 2014 International Workshop on EUV and Soft X-Ray Sources in Dublin, Ireland.

5th annual source workshop is now the largest annual gathering of EUV and XUV source experts and continues to grow. This workshop will continue to 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, 2014 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

Monday, November 3, 2014

Location: Newman House, Stephen's Green, Dublin

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

Tuesday, November 4, 2014

Location: George Moore Auditorium, UCD Campus, Dublin

7:45 AM	Pickup at the Hotel (Stephen's Green and Mesphil Hotel)
8:30 AM – 12:00 PM	Workshop Presentations
12:00 PM - 1:00 PM	Lunch
1:00 PM – 5:30 PM	Workshop Presentations
5:30 PM – 6:45 PM	Poster Session and Reception
7:00 PM	Depart for Off-Site Dinner (Pickup at Auditorium)

Wednesday, November 5, 2014

Location: George Moore Auditorium, UCD Campus, Dublin

7:45 AM	Pickup at the Hotel (Stephen's Green and Burlington)
8:30 AM – 12:40 PM	Workshop Presentations
12:40 PM -1:40 PM	On-site Lunch
1:40 AM – 3:30 PM	Workshop Presentations
3:45 PM	Depart for tour
	(Pickup at the Auditorium)

Thursday, November 6, 2014

Location: Newman House, Stephen's Green, Dublin

Technical Working Group (TWG) Meeting

8:30 AM – 10:00 AM	TWG Meeting

WORKSHOP AGENDA

2014 International Workshop on EUV and Soft X-Ray Sources

November 3-6, 2014, Dublin, Ireland

Monday, November 3, 2014 (Newman House)

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

Tuesday, November 4, 2014 (George Moore Auditorium)

8:30 AM Announcements and Introductions

Introduction and Announcements (Intro-1)

Vivek Bakshi, EUV Litho, Inc., USA

8:40 AM Session 1: Keynote Session -1

Session Chair: Padraig Dunne

EUVL for HVM: Progress and Risks (S1)

Mark Phillips
Intel Corporation

One Hundred Watt Class EUV Source Development for HVM Lithography (S2)

Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Takeshi Ohta, 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: 3-25-1 Shinomiya Hiratsuka Kanagawa, 254-8567, JAPAN

Awards and Announcements – Padraig Dunne (UCD)

Break 10:00 AM

10:20 AM Session 2: HVM EUV Sources

Session Co-Chairs: Wim Zande (ASML) and Stephen Horne (Energetiq)

EUV Sources for HVM Scanners: Status Update and Roadmap (Tentative title) (Invited) (S29)

Wim van der Zande
ASML

Measurement of CO_2 laser absorption by tin plasma as a 13.5 nm EUV light source (S23)

H. Nishimura, H. Matsukuma, K. Yoshida, T. Hosoda, A. Yogo, N. Tanaka, S. Fujioka, K. Nishihara, A. Sunahara[*], and T. Somekawa[*]
Institute of Laser Engineering, Osaka University, Japan
[*] *Institute for Laser Technology, Japan*

Droplet-based EUV LPP Source for High Volume Metrology (S30)
Bob Rollinger, Nadia Gambino, Andrea Giovannini, Duane Hudgins, Alexander Sanders and Reza S. Abhari
Laboratory for Energy Conversion, Swiss Federal Institute of Technology Zurich (ETHZ), Switzerland

Femtosecond laser pre-pulse technology for LPP EUV source (S72)

Alexander Vinokhodov[1], Vladimir Krivtsun[1,2], Mikhail Krivokorykov[1],Yury Sidelnikov[1,2], Sergey Chekalin[2], Victor Kompanets[2] , Alexey Melnikov[2], Konstantin Koshelev[1,2]
[1] *EUV Labs/RnD ISAN, Moscow, Russia,*
[2] *Institute for Spectroscopy RAS, Moscow, Russia*

Evolution of the Energetiq Electrodeless Z-Pinch™source – What worked, and what didn't… (Invited) (S73)

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

Energetiq Technology Inc., Woburn, MA, USA

Source Requirements for Next Generation AIMS EUV (Invited) (S94) (10 minutes short presentation)

Udo Dinger
Carl Zeiss

Metrology source requirements for KLA Actinic Inspection Tool (Invited) (S93) (10 minutes short presentation)

Oleg Khodykin
KLA-Tencor

Metrology Source Requirements for Actinic Mask Blank Inspection (Invited) (S95) (10 minutes short presentation)

Stephen F. Horne
Energetiq

Lunch 12:00 PM

1:00 PM Session 3: Modeling

Session Chair: Gerry O'Sullivan (UCD)

Computer simulation tools for plasma-based sources of EUV radiation (Invited) (S35)

V. V. Medvedev[1,2], V. G. Novikov[1,3], V. V. Ivanov[1,2], I. Yu. Vichev[1,3], M.M. Basko[1,3], V. S. Konovalov[1,3], A. D. Solomyannaya[1,3], A. S. Grushin[1,3], , A. M. Yakunin[4], A. Bratchenia[4], D. Labetski[4], K. Feenstra[4] and K. N. Koshelev[1,2]
[1] *RnD-ISAN/EUV Labs, Moscow, Troitsk, Russia*
[2] *Institute for Spectroscopy RAS, Moscow, Troitsk, Russia*
[3] *Keldysh Institute of Applied Mathematics RAS, Moscow, Russia*
[4] *ASML Netherlands, Veldhoven, The Netherlands.*

Hydrodynamics modeling of the dynamics of Sn droplet target for the EUV source (S31)

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

Radiation hydrodynamics of tin targets for laser-plasma EUV sources (S36)

Mikhail Basko

KIAM, Moscow, Russia

2:00 PM Session 4: FEL-1

Session Co-Chairs: Akira Endo (HiLase and Waseda University) and Hironari Yamada (Ritsumeikan University)

Expectation and challenges of higher NA EUV lithography (Invited) (S57)

Takayuki UCHIYAMA
Lithography Process Development Department, Center for Semiconductor Research and Development, TOSHIBA Corporation

Optimization of high average power FEL beam for EUV lithography application (Invited) (S51)

Akira Endo[1,2], Kazuyuki Sakaue[1], Masakazu Washio[1] and Hakaru Mizoguchi[3]
[1]Research Institute for Science and Engineering, Waseda University, [2]HiLase Center, [3]Gigaphoton Inc.

High efficiency 10 kW class FEL for EUV lithography (Invited) (S52)

Alex Murokh
RadiaBeam Technologies, LLC, USA

Development of Superconducting Accelerator with ERL for EUV-FEL (Invited) (S55)

Eiji Kako
KEK, High Energy Accelerator Research Organization, JAPAN

Break and Group Photogrpah 3:20 PM (20 Minutes)

3:40 PM Session 5: FEL-2

Session Co-chairs: Alex Murokh (RadiaBeam Technologies) and Mikhail Yurkov (DESY)

Accelerator technologies for EUV or Soft X-ray Lithography (S60) (Invited – Review Talk)

Hironari Yamada
Ritsumeikan University, Japan

The FERMI free electron laser soft – x-ray user facility (S54) (Invited)

E. Allaria
FERMI commissioning team

Design of High-Power Free-Electron Lasers for EUV Lithography Applications (S56) (Invited)

Ryoichi Hajima [1), 2)]
1) Japan Atomic Energy Agency, Tokai, Naka, Ibaraki 3191195 Japan
2) High Energy Accelerator Research Organization, Tsukuba, Ibaraki 3050801 Japan

Status, perspectives, and lessons from FLASH (S58) (Invited)

E. A. Schneidmiller, M. V. Yurkov
Deutsches Elektronen Synchrotron (DESY), Hamburg, Germany

5:30 PM – 6:45 PM Session 6: Poster Session (Poster Listings – Next Page)

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

End of Day 2

5:30 PM Session 6: Poster Session

Session Chair: Padraig Dunne (UCD)

Topic: EUV Sources for HVM

Efficient EUV sources by short CO_2 laser-produced plasmas (S21)

Reiho Amano[1], Thanh Hung Dinh[1], Masato Kawasaki[1], Atsushi Sasanuma[1], Yuhei Suzuki[1], Takeshi Higashiguchi[1], and Taisuke Miura[2]

[1]Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan
[2]HiLASE Centre, Institute of Physics ASCR, v.v.i., Za Radnici 828, 25241 Dolni Brezany, Czech Republic

A microplasma high-brightness EUV source at 13.5 nm (S22)

Goki Arai[1], Hiroyuki Hara[1], Yuhei Suzuki[1], Thanh Hung Dinh[1], and Takeshi Higashiguchi[1]
[1]Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE) Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan

Long-term Confinement of Dense Plasma Column by Magnetic Field of Vertical Current Loop in Discharge Plasma of EUV Source (S25)

N. A.Azarenkov, Ie. V. Borgun, V. I. Maslov, D. L. Ryabchikov, A. F. Tseluyko, I. P. Yarovaya
Karazin Kharkov National University, Kharkov, Ukraine

Time resolved Imaging & EUV spectroscopy studies on laser-assisted vacuum-arc EUV source (S26)

Girum Abebe Beyene[1,3], Isaac Tobin[2], Larissa Juschkin[3], Padraig Dunne[1], Emma Sokell[1] , Gerry O’Sullivan[1], and Fergal O'Reilly[1]
[1]School of Physics, University College Dublin, Ireland,
[2]School of Physics, Trinity College Dublin, Dublin 2, Ireland
[3]Department of Physics, RWTH Aachen University, Aachen, Germany

Study on Extreme Ultraviolet Light Source Radiated by Capillary Discharge Produced Xe Plasma with Repetition Rate of 1kHz (S27)

Zhao Yongpeng[1], Xu Qiang[2,1], Li Qi[1], Wang Qi[1]
[1]National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150080, China
[2]College of science, Northeast forestry university, Harbin 150040, China

EUV contamination control at TNO (S28)

Edwin te Sligte, Arnold Storm, Norbert Koster, Jacques van der Donck, Michel van Putten, Jetske Stortelder, Herman Bekman, Daan van Eijk, Rob Ebeling, Freek Molkenboer, Véronique de Rooij, Jacqueline van Veldhoven, Jochem Janssen
TNO, Delft, The Netherlands

LPP Light Source for Metrology and Inspection Applications (S71)

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

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

Topic: Modeling

Modeling of target deformations due to pre-pulse with debris analysis (S32)

I. Yu. Vichev[1,3], V. G. Novikov[1,3], M.M. Basko[1,3], V.V. Ivanov[1,2], V.V. Medvedev[1,2]
[1] RnD-ISAN, Troitsk, 142190 Russia
[2] Institute of Spectroscopy RAS, Troitsk, 142090 Russia
[3] Keldysh Institute of Applied Mathematics RAS, Moscow, 125047 Russia

Radiation hydrodynamic simulation of a high-brightness 13.5-nm EUV microplasma (S33)

Hiroyuki Haya[1], Goki Arai[1], Takanori Miyazaki[1], Thanh-Hung Dinh[1], Takeshi Higashiguchi[1], and Atsushi Sunahara[2]
[1]Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan
[2]Institute for Laser Technology, 2-6 Yamada-Oka, Suita, Osaka 565-0871 Japan

Plasma source modeling accounting non-LTE radiation transport and level kinetics in-line with gasdynamics (S34)

D.A. Kim, V.G. Novikov, G.V. Dolgoleva, A.D. Solomyannaya
Keldysh Institute of Applied Mathematics RAS, Moscow, Russia

Model for plasma debris mitigation by gaseous atmosphere (S37)

V. Konovalov
ISAN, Moscow, Russia

Validation of EUV source models against experimental simulations (S39)

V. Grushin
ISAN, Moscow, Russia

3D SIMULATION OF SHIFTED LASER PULSE COUPLING TO TIN TARGET (S40)

I.P. Tsygvintsev, A.Yu.Krukovskiy, V.G. Novikov
KIAM RAS, Moscow, Russia

Topic: FEL

Development of High Repetition Rate Seed Pulse at 324nm for EUV-FEL using Picosecond Thin-disk Regenerative Amplifier (S53)

Taisuke Miura[1], Michal Chyla[1,2], Martin Smrž[1], Siva Sankar Nagisetty[1,2], Patricie Severová[1,2], Ondřej Novák[1], Hana Turčičová[1], Pawel Sikocinski[1,2], Akira Endo[1,3], and Tomáš Mocek[1]
[1]*HiLASE Centre, Institute of Physics ASCR, Za Radnicí 828, 252 41 Dolní Břežany, Czech Republic*
[2]*Czech Technical University in Prague, Břehová 7, 115 19, Prague, Czech Republic*
[3]*Waseda University, 17 Kikui-cho Shinjuku Tokyo, Japan*

Optimization of a high efficiency FEL amplifier (S59)

E.A. Schneidmiller, M.V. Yurkov
Deutsches Elektronen Synchrotron (DESY), Hamburg, Germany

Topic: Optics

Controlling interface chemistry in 6 nm La/B multilayer optics (S84)

Dmitry Kuznetsov, Marko Sturm, Robbert van de Kruijs, Andrey Yakshin, Eric Louis and Fred Bijkerk
MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

Topic: Soft X-ray Sources and Applications

Quasi-Moseley's law for UTA spectra in high-Z highly ion charge states for high power EUV & soft x-ray sources (S43)

Yuhei Suzuki[1], Goki Arai[1], Takanori Miyazaki[1], Thanh-Hung Dinh[1], and Takeshi Higashiguchi[1]
[1]Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan

Nanometer optical coherence tomography using broadband extreme ultra violet light (S44)

S. Fuchs[1,2], C. Rödel[1,2], M. Wünsche[1,2], J. Biedermann[1], U. Zastrau[1], V. Hilbert[1], E. Förster[1], G. G. Paulus[1,2]
[1] Institute of Optics and Quantum Electronics, Friedrich Schiller University Jena, Germany
[2] Helmholtz Institute Jena, Germany

Comparison of Laser Produced Plasma and Discharge Produced Plasma as a Source for Soft X-Ray Microscopy (S48)

T. Parkman[1], S. Vondrova[1], M. Nevrkla[2], P. Bruza[1], M. Vrbova[1]
[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

Laser-Produced Plasma Spectroscopy of Medium to High-Z Elements in the 2 to 10 nm Spectral Region (S49)

Elaine Long[1], John Sheil[1], Elgiva White[1], Chihiro Suzuki[2], Padraig Dunne[1], Fergal O'Reilly[1] & Gerry O'Sullivan[1]
[1]UCD School of Physics, University College Dublin,Belfield, Dublin 4, Ireland.
[2]National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

Investigation of Laser-Produced Plasmas of Mo, Ru, Rh and Pd in the 2.4 nm to 13 nm Spectral Region (S50)

Ragava Lokasani[1,2], Elaine Long[1], Girum Beyene[1], Patrick Hayden[1], Padraig Dunne[1], Jiri Limpouch[2], Akira Endo[3], Fergal O'Reilly[1] &Gerry O'Sullivan[1]
1) UCD School of Physics, University College Dublin, Belfield, Dublin 4, Ireland.
2) Czech Technical University, Prague, Czech Republic
3) HiLASE Project, Prague, Czech Republic

Characteristics of soft x-ray emission from optically thin high-*Z* plasmas in Large Helical Device (S92)

Hayato Ohashi[1], Takeshi Higashiguchi[2], Yuhei Suzuki[2], Goki Arai[2], Bowen Li[3], Padraig Dunne[4], Gerry O'Sullivan[4], Hiroyuki A. Sakaue[5], Daiji Kato[5], Izumi Murakami[5], Naoki Tamura[5], Shigeru Sudo[5], Fumihiro Koike[6], and Chihiro Suzuki[5]
[1]Graduate School of Science and Engineering for Research, University of Toyama, Toyama, Toyama 930-8555, Japan
[2]Department of Advanced Interdisciplinary Sciences and Center for Optical Research and Education (CORE), Utsunomiya University, Utsunomiya, Tochigi 321-8585, Japan
[3]School of Nuclear Science and Technology, Lanzhou University, Lanzhou, 730000, China
[4]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland
[5]National Institute for Fusion Science, Toki, Gifu 509-5292, Japan
[6]Faculty of Science and Technology, Sophia University, Chiyoda, Tokyo 102-8554, Japan

Topic: Water-window Microscopy

Possibility of high-*Z* plasma water window sources (S61)

Takanori Miyazaki[1], Yuhei Suzuki[1], Thanh Hung Dinh[1], and Takeshi Higashiguchi[1]
[1]*Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan*

Wednesday, November 5, 2014

8:30 AM Announcements

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

8:40 AM Session 7: Keynote Session - 2

Session Chair: Padraig Dunne (UCD)

Tomographic Imaging with Soft X-rays (S3)

Carolyn Larabell
University of California, San Francisco

9:20 AM Session 8: Optics

Session Co-chairs: Torsten Feigl (optiX fab) and Eric Louis (DIFFER)

Multilayer collector mirror for DPP EUV metrology sources (S82) (Invited)

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

Spectral purity enhancement for the EUV Lithography Systems (S83) (Invited)

Eric Louis[a,b], Qiushi Huang[a,b], Slava Medvedev[a,b], V. M. Krivtsun[c], Meint de Boer[a], *Robbert van de Kruijs[a,b], and Fred Bijkerk[a,b]*
[a] *MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE, Enschede, The Netherlands*
[b] *FOM Institute DIFFER - Dutch Institute for Fundamental Energy Research, P.O. Box 1207, 3430 BE, Nieuwegein, The Netherlands*
[c] *Institute for Spectroscopy RAS, Fizicheskaya Str. 5, Troitsk, Moscow Region, 142190 Russia*

Possible beam expander and homogenizer for 13.5 nm applications (S81) (Invited)

Ladislav Pina
Czech Technical University in Prague, CR

Damage to optics under irradiations with the intense EUV FEL pulses (S85) (Invited)

Ryszard Sobierajski[1], Eric Louis[2]
Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, PL-02-668 Warsaw, Poland
Universiteit Twente, TNW-XUV Optics, Drienerlolaan 5, 7522 NB Enschede, The Netherlands

10:40 AM Break (20 minutes)

11:00 AM Session 9: Soft X-ray and Applications

Session Co-chairs: Ladislav Pena (Czech Technical University) and Larrisa Jushkin (RWTH Aachen University)

A New Setup for Observation of Forbidden Lines from Metastable Ions produced in Charge Exchange Collisions (S41)

Hajime Tanuma[A] , Naoki Numadate[B], Hirofumi Shimaya[A] , Nubuyuki Nakamura[C], Kunihiro Okada[B]
[A] *Department of Physics, Tokyo Metropolitan University, 1-1 Minani-Ohsawa, Hachioji, Tokyo 192-0397, Japan*
[B] *Department of Physics, Sophia University, 7-1 Kioicho, Chiyoda, Tokyo 102-8554, Japan*
[C] *Institute for Laser Science, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-0021, Japan*

EUV Ablation of PPEES: Process and Critical Factors (S42)

C. Liberatore[1,2], A. Bartnik[4], K. Mann[3], M. Müller[3], L. Pina[2], L. Juha[1], J. J. Rocca[5], A. Endo[1], T. Mocek[1]
[1]HiLASE Project, Institute of Physics ASCR, Dolní Břežany, Czech Republic;
[2]Czech Technical University, Prague, Czech Republic;
[3]Institute of Optoelectronics (IOE) ,Military University of Technology, Warsaw, Poland;
[4]Laser Laboratorium Göttingen (LLG), Göttingen, Germany;
[5]Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO 80523, USA

Coherent Extreme ultra violet Light Sources using Highly Efficient High Harmonic Generation (S45)

M. Wünsche[*1,2], A. Hage[3,4], M. Taylor[4], M. Yeung[2,4], C. Rödel[1,2], B. Landgraf[1,2], A. Willner[3], M. J. Prandolini[2], M. Schulz[3], T. Gangolf[1], S. Fuchs[1,2], H. Höppner[3], R. Riedel[2], B. Dromey[4], F. Tavella[2], C. Spielmann[1], M. Zepf[1,2,4], G. G. Paulus[1,2]

[1] Institute of Optics and Quantum Electronics, Friedrich Schiller University Jena, Germany
[2] Helmholtz Institute Jena, Germany
[3] Deutsches Elektronen Synchrotron, Germany
[4] Queen's University Belfast, United Kingdom

Laser Plasma Monochromatic Soft X-ray Source Using Nitrogen Gas Puff Target (S47)

M. Vrbova[1], P. Vrba[2], S.V. Zakharov[3], V.S. Zakharov[4], M. Müller[5], D. Pánek[1], T. Parkman[1]
[1]Czech Technical University, Faculty of Biomedical Engineering, 272 01 Kladno, CR,
[2]Institute of Plasma Physics, Czech Academy of Sciences, 182 00 Prague 8, CR,
[3]NaextStream sas, Buc, France, 4KIAM RAS, Moscow, Russia, 5LLG, D-37077 Göttingen

Source Radiance Requirements for High Resolution Imaging and Interference Techniques (S91) (Invited)

Larissa Juschkin
RWTH Aachen University, Germany

12:40 PM Lunch

1:40 PM Session 10: Water Window Microscopy

Sources for Water Window Imaging (S64) (Invited Review Talk)

Gerry O'Sullivan[a], Padraig Dunne[a], Paddy Hayden[a], Bowen Li[ab], Ragava Lokasani[ac], Elaine Long[a], Hayato Ohashi[d], Fergal O'Reilly[a], John Sheil[a], Emma Sokell[a], Chihiro Suzuki[e], Elgiva White[a] and Takeshi Higashiguchi[f]
[a]*School of Physics, University College Dublin, Belfield, Dublin 4, Ireland*
[b]*School of Nuclear Science and Engineering, Lanzhou University, Lanzhou 730000, China*
[c]*Czech Technical University, Brehova 7,Czech Republic*
[d]*University of Toyama,3190 Gofuku, Toyama, Toyama 930-8555, Japan*
[e]*National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan*
[f]*Utsunomiya University, 7-1-2 Yoto, Utsunomiya 321-8585, Japan*

Water window radiation from 40 kA Z-pinching capillary discharge plasma (S62)

Michal Nevrkla and Alexandr Jančárek
Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Czech Republic

3D Characterization of Chromatin Structure (S65) (Invited)

M Myllys[1], C Larabell[2], J Timonen[1] and M. Vihinen-Ranta[1]
[1] *University of Jyväskylä, Department of Physics, Jyväskylä, Finland*
[2] *Department of Anatomy, University of California, San Francisco, USA*
[3] *Physical Biosciences Division, Lawrence Berkeley National Laboratory, Berkeley, USA*

Soft X-ray Source for High-speed Soft X-ray Tomography of Cryo-frozen Cells (S63)

Fergal O'Reilly, Kenneth Fahy, Padraig Dunne, Niall Kennedy, Paul Sheridan
School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

3:10 PM Workshop Summary and Announcements

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

3:30 PM Workshop Adjourned

3:30 PM Leave for Tour (TBA)

Thursday, November 6, 2014

Location: Newman House, Stephen's Green, Dublin

Technical Working Group (TWG) Meeting

8:30 AM – 10:00 AM TWG Meeting

ABSTRACTS

S1

EUVL for HVM: Progress and Risks

Mark Phillips

Intel Corporation

Progress on EUV exposure tools and sources in the last year--while not meeting the supplier's original schedule--has generally proceeded as expected by potential end users of the technology. Several 0.33 NA scanners have shipped to wafer fabs, with performance meeting imaging, overlay and other non-productivity-related specifications. Sources for these tools are operating in the long-awaited MOPA/PrePulse mode required for high conversion efficiency, and are delivering ~40 W to the input of the scanner illuminator while meeting dose control requirements. Raw wafer throughput of tools in the field is consistent with the tool design at this source power.

While these power and productivity levels are far from the final targets for the technology (and well below what is required for cost-effective manufacturing) they represent an important demonstration of performance beyond the expectations of many skeptics of the technology. As predicted last year, this progress has triggered a re-evaluation of the state of the larger EUV infrastructure, and the realization that the introduction of EUV Lithography into High Volume Manufacturing (HVM) could be gated by other infrastructure readiness, rather than scanner and source performance.

As the scanner supplier works towards delivering productivity, availability and operational expenses consistent with cost-effective HVM, the semiconductor industry needs to work on a well-known list of supporting technologies that have become a schedule risk mainly due to reluctance to commit resources while source power was stuck below 10W. Specifically: mask blank defect reduction and manufacturing capacity; bright, stable EUV sources for actinic mask metrology tools; development of mask inspection tools (blanks, aerial image, and pattern); and commercialization of full-field EUV pellicles.

Presenting Author

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

S2

One Hundred Watt Class EUV Source Development for HVM Lithography

Hakaru Mizoguchi, Hiroaki Nakarai, Tamotsu Abe, Takeshi Ohta, 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: 3-25-1 Shinomiya Hiratsuka Kanagawa, 254-8567, JAPAN

Presenting Author

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

He is a 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 CO_2 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 F_2 laser research and development for lithography application. He was general manager of research division in Komatsu Ltd. until 1999. He got PhD 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 under his present position.

S3

Tomographic Imaging with Soft X-rays

Mark A. Le Gros[1,2] and Carolyn A. Larabell[1,2]

[1.] *Dept. of Anatomy, University of California San Francisco, San Francisco USA*
[2.] *Physical Biosciences Division, Lawrence Berkeley National Laboratory, Berkeley USA*

Soft X-ray tomography (SXT) is similar in concept to the well-established medical diagnostic technique, computed axial tomography (CAT), except SXT is capable of imaging with a spatial resolution of 50 nm or better. Images are formed using unique optics called zone plates (ZP). An X-ray ZP optic consists of a number of concentric nanostructured metal rings, or zones, formed on a thin X-ray transmissive silicon nitride membrane. The width of the outermost ring determines the spatial resolution of the ZP lens, whereas the thickness of the rings determines the focusing efficiency. By collecting images from multiple angles through 180 degrees of rotation, SXT reconstructions yield information at isotropic resolution. We are using SXT to examine whole, hydrated biological cells (between 10-15 μm thick), which eliminates the need for artifact-inducing and time-consuming embedding and sectioning procedures. To image cells, we use X-ray energies between the K shell absorption edges of carbon (284 eV, λ=4.4 nm) and oxygen (543 eV, λ=2.3 nm). In this energy range, photons readily penetrate the aqueous environment while encountering significant absorption from carbon- and nitrogen-containing organic material. Since X-ray absorption follows Beer's Law, the absorption of photons is linear and a function of the biochemical composition at each point in the cell. To determine the location of specific molecules with respect to cellular structures, we overlay molecular information obtained with fluorescence microscopy of a cell on the structural information obtained with x-ray tomography of the same cell. I will present examples of a number of cell types imaged using SXT.

Presenting Author

Carolyn Larabell holds a joint position as Professor in the Department of Anatomy at the University of California, San Francisco School of Medicine, and Faculty Scientist in the Physical Biosciences Division at the Lawrence Berkeley National Laboratory. She is also Director of the UCSF/LBNL National Center for X-ray Tomography. Dr. Larabell received her Ph.D. from Arizona State University in 1988 and did postdoctoral training at Stanford University and at the University of California at Davis. She has been at Lawrence Berkeley National Laboratory since 1990, was appointed Advanced Light Source Professor at LBNL in 1999 and Professor in the Department of Anatomy at UCSF in 2000.

Dr. Larabell's research interests center on the development of novel imaging techniques and their application to cell and developmental biology, including events involved with chromatin organization during cell differentiation. She has extensive experience with a variety of imaging technologies including electron microscopy; freeze-fracture and quick-freeze, deep-etch, rotary-shadow TEM; confocal and multi-photon microscopy, and super-resolution fluorescence microscopy. Since 1997 she has been leading the efforts at Lawrence Berkeley National Laboratory to develop soft x-ray microscopy for imaging biological cells and in 2004 established the National Center for X-ray Tomography (NCXT), a National Institutes of Health Biomedical Technology Research Center.

S21

Efficient EUV Sources by Short CO_2 Laser-produced Plasmas

Reiho Amano[1], Thanh Hung Dinh[1], Masato Kawasaki[1], Atsushi Sasanuma[1], Yuhei Suzuki[1],
Takeshi Higashiguchi[1], and Taisuke Miura[2]

[1]Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan
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We develop the hybrid laser system with the sub-nanosecond laser and TEA CO_2 laser amplifier to produce the short pulse and high energy pulses at a wavelength of 10.6 μ. We will report the preliminary experimental results of the extreme ultraviolet sources from the short CO_2 laser-produced plasmas (LPPs).

Presenting Author

Reiho Amano is a Ph.D. student in Utsunomiya University. He works in Carl Zeiss Japan. His research activities have focused on Efficient EUV sources by short pulse and high energy CO_2 lasers.

S22

A Microplasma High-brightness EUV Source at 13.5 nm

Goki Arai[1], Hiroyuki Hara[1], Yuhei Suzuki[1], Thanh Hung Dinh[1], and Takeshi Higashiguchi[1]

[1]Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE) Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan

We report the effect of irradiation of solid Sn targets with laser pulses of sub-ns duration and sub-mJ energy on the diameter of the extreme ultraviolet (EUV) emitting region and source conversion efficiency. It was found that an in-band EUV source diameter as low as 18 □m was produced due to the short scale length of a plasma produced by a sub-ns laser. Most of the EUV emission occurs in a narrow region with a plasma density close to the critical density value. Such EUV sources are suitable for high brightness and high repetition rate metrology applications.

Presenting Author

Goki Arai is a master course student in Utsunomiya University. His research activity has focused on high brightness EUV source for actinic mask inspection and metrology in next generation semiconductor lithography.

S23

Measurement of CO_2 Laser Absorption by Tin Plasma as a 13.5 nm EUV Light source

H. Nishimura, H. Matsukuma, K. Yoshida, T. Hosoda, A. Yogo, N. Tanaka, S. Fujioka
Nishihara, A. Sunahara*, and T. Somekawa*

Institute of Laser Engineering, Osaka University, Japan
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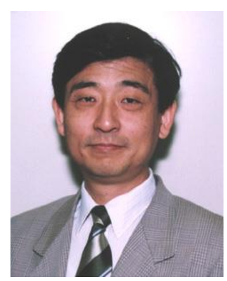
Laser-driven tin plasma has been studied as a light source of extreme ultraviolet (EUV) at 13.5 nm (+/- 1 % in-band width) for the next-generation semiconductor manufacturing. By using CO_2 laser as a driver, high conversion efficiency (CE) has been attained in previous works by optimizing optical thickness for EUV radiation. Radiation hydrodynamic simulation predicts, however, that absorption coefficient for CO_2 laser is as high as 50 % for a tin plasma generated with a single laser pulse mainly due to short plasma scale. The relatively low absorption is a crucial problem for efficient generation of EUV light. 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. Therefore, it is important to measure CO_2 laser absorption rate precisely in order to optimize plasma conditions. For this purpose we designed an integrating sphere for CO_2 laser. Laser absorption was measured for tin plasmas generated under various conditions including target geometries. We will show experimental results and discuss on guidelines for getting higher CE.

Presenting Author

Professor of Institute of Laser Engineering (ILE), Osaka University, Japan. He has been engaged in scientific researches of laser plasma physics and applications including laser-driven nuclear fusion and laser plasma radiations for more than 30 years. He has authored over 260 journal papers including 42 papers on EUV generation and applications for material science.



S25

LONG-TERM CONFINEMENT OF DENSE PLASMA COLUMN BY MAGNETIC FIELD OF VORTICAL CURRENT LOOP IN DISCHARGE PLASMA OF EUV SOURCE

N. A. Azarenkov, Ie. V. Borgun, V. I. Maslov, D. L. Ryabchikov, A. F. Tseluyko, I. P. Yarovaya

Karazin Kharkov National University, Kharkov, Ukraine

The existence of significant plasma parameters, almost unchanged for long time, much longer than period of discharge was observed in several experiments [1-3] in high-current gas discharge. It may be due to the formation of the Rossby vortex in the region occupied by the plasma column. Formation of such half-vortex [4] and vortex [5] was observed in the vicinity of the foil due to the interaction of the laser pulse with it. Also two contacting half-vortices were observed in the vicinity of the foil due to the interaction with it two close (neighboring) laser pulses [6]. Similar vortex was observed in gas-discharge plasma. Properties, formation and the role of the vortex formation in dense discharge plasma are investigated in this work. It is shown that the magnetic field of the vortex provides long existence of the vortex with the same direction of rotation and long-term self-confinement of dense plasma column.

1. V. A.Kiselev. Thesis of DrSc.
2. I. P. Skoblik. Investigation of influence of initial gas conditions in co-axial accelerator on parameters of plasma bunches. PhD Thesis. 1972.
3. A. F. Tseluyko, V. T. Lazurik, D. L. Ryabchikov, V. I. Maslov, and I. N. Sereda. Experimental Study of Radiation in the Wavelength Range 12.2–15.8 nm from a Pulsed High-Current Plasma Diode. Plasma Physics Reports, 2008, V. 34, N 11, P. 963–968.
4. M. Borghesi, *et al.,* Fusion Science and Technology, 49, 412 (2006)
5. S.V.Bulanov, T.Zh.Esirkepov. *PRL.* 2007. V. 98. P. 049503.
6. P. M. Nilson, L. Willingale, M. C. Kaluza et al. Magnetic Reconnection and Plasma Dynamics in Two-Beam Laser-Solid Interactions. PRL. 2006. V. 97**, P.** 255001.

Presenting Author

S26

Time resolved Imaging & EUV Spectroscopy Studies on Laser-Assisted Vacuum-arc EUV Source

Girum Abebe Beyene[1,3], Isaac Tobin[2], Larissa Juschkin[3], Padraig Dunne[1], Emma Sokell[1] , Gerry O'Sullivan[1], and Fergal O'Reilly[1]

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[2]School of Physics, Trinity College Dublin, Dublin 2, Ireland
[3]Department of Physics, RWTH Aachen University, Aachen, Germany

EUV light sources has remained among the major bottlenecks for the delay of high-volume manufacturing with EUVL. Major drawbacks of traditional DPP sources are low conversion efficiency (CE) and high associated heat load compared to LPP. The hybrid Laser-triggered Discharge Plasma (LDP) source combines the scalability and stability features of DPPs with high CE of LPPs. The present report substantiates this claim by providing experimental demonstration from laser triggered discharge ignited between liquid-tin-coated rotating electrodes. The EUV power was found to depend strongly on parameters of the localized laser ablation of the liquid tin-layer. This was studied by tailoring laser parameters, mainly the pulse duration and energy density, using two Nd:YAG lasers, of 1064 nm wavelength and pulse durations ~160 ps and ~7 ns. Both reach intensity in the range of ~3-300 GW/cm^2.

Our time resolved imaging & EUV spectroscopy results indicated that the picosecond (ps)-laser produces higher CE and spectral purity compared to ns-triggering. This is attributed mainly to the different expanding plasma dynamics. The ps-laser produced plasma is better collimated and has higher axial speed than the ns-plasma which improved the stability of the discharge.

Presenting Author

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

S27

Study on Extreme Ultraviolet Light Source Radiated by Capillary Discharge Produced Xe Plasma with Repetition Rate of 1 k Hz

Zhao Yongpeng[1], Xu Qiang[2,1], Li Qi[1], Wang Qi[1]

[1]National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150080, China
[2]College of science, Northeast forestry university, Harbin 150040, China

The extreme ultraviolet (EUV) light source with repetition rate of 1kHz was built, which is based on capillary discharge produced Xe plasma. In the structure of discharge system, the water cooling electrodes and the Al_2O_3 capillary with length of 6mm and inner diameter of 3-5mm were used. In order to produce a narrow main pulse, three stage magnetic pulse compression was employed in the main pulse power supply. The power supply has been adjusted with fictitious load and capillary load. The main pulse with voltage amplitude of 22kV, current amplitude of 14kA, first half cycle duration of ~200ns has been achieved. In experiment, the EUV emission at 13.5nm has been realized with Xe^{10+} by discharge through Xe gas in capillary. The influence of experimental parameters, such as gas flow rate, on EUV intensity at 13.5nm has been measured, and the optimum parameters have been obtained.

Presenting Author

Zhao Yongpeng was born in Heilongjiang Province, China, on September 17, 1973. He received Ph. D. degree in physical electronics from Harbin Institute of Technology in 2001, and is presently a professor at Harbin Institute of Technology.

Much of Zhao's work has been in short wavelength laser and extreme ultraviolet (EUV) light source. He has worked on ionic excimer excited by electron beam, soft x-ray laser excited by capillary discharge and discharge produced plasma EUV source. He has observed the resonator effect of argon ionic excimer. Two soft x-ray lasers pumped by capillary discharge with different current waveforms have been built by his group. The saturated soft x-ray laser at 46.9 nm was generated and the new-wavelength lasers at 69.8nm and 72.6 nm in Ne-like Ar ions were firstly demonstrated. In addition, his group has built the EUV light source with Xe plasma produced by capillary discharge.

S28

EUV Contamination Control at TNO

Edwin te Sligte, Arnold Storm, Norbert Koster, Jacques van der Donck, Michel van Putten, Jetske Stortelder, Herman Bekman, Daan van Eijk, Rob Ebeling, Freek Molkenboer, Véronique de Rooij, Jacqueline van Veldhoven, Jochem Janssen

TNO, Delft, The Netherlands

Contamination control and component lifetime assurance are key enabling technologies for EUV lithography. TNO has an extensive track record on this topic, including source contamination and plasma-surface-materials interaction. The EUV contamination-control program for example has been running at TNO for over ten years. The overall program goal is to support the introduction and development of EUV lithography. We show here a few examples of our work applicable to EUV source development.

Presenting Author

S29

EUV Sources for HVM Scanners : Status Update and Roadmap (Tentative title)

Wim van der Zande

ASML, The Netherlands

Presenting Author

Wim van der Zande studied in parallel experimental physics and biochemistry at the University of Amsterdam. He obtained his PhD in physics on a subject in molecular physics from the University of Amsterdam under Prof J. Los, director of the FOM Institute AMOLF. After a postdoc at Stanford University in the group of prof R. Zare, he returned to the FOM Institute AMOLF in 1991 starting a group on molecular physics, atmospheric physics and instrumentation. In 2003 he moved as full professor at the Radboud University Nijmegen in molecular and laser physics. In 2006 his group became responsible for constructing a far infrared free electron laser as part of a user facility. First lasing was achieved in 2011. Among other functions, he was member of the board of the Netherlands Institute for Space Research from 2000 to 2014. In August 2014 he joined ASML as Director of Research in the group Physics and Chemistry, responsible for competences around laser produced plasma sources, resist, and material science properties in lithography.

S30

Droplet-based EUV LPP Source for High Volume Metrology

Bob Rollinger, Nadia Gambino, Andrea Giovannini, Duane Hudgins, Alexander Sanders and Reza S. Abhari

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

At the Laboratory for Energy Conversion (LEC), ETH Zurich, prototype EUV sources for actinic metrology have been designed, developed and tested over the last years. The source's targets are micrometer tin droplets that are irradiated by a 1.6 kW Nd:YAG laser. A peak brightness of 350 W/mm^2sr is achieved. Recent achievements on the latest prototype source ALPS II include a EUV emission pulse-to-pulse stability of 3% (σ). EUV collection optics and an intermediate focus (IF) module have been added to the source. The latest source performance results with respect to EUV emission and cleanliness after IF will be presented. We also provide an update on source performance for our newly implemented droplet irradiation scheme. Another topic of this presentation will be the extension of the operating time to 24/7. An overview of recent research achievements from the ALPS program, which includes angular debris measurements, will be given together with future perspectives. Adlyte is in the process of commercializing the technology.

Presenting Author

S31

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

Novel pumping schemes have been studied to improve the output power and efficiency of the laser plasma pumped (LPP) EUV source. Using the double-pulse pumping scheme, the Sn droplet target is broken up into particles by the first laser pulse and is heated to high temperature to obtain EUV emission by the second laser pulse. The average density of the plasma is low with this scheme, which is preferred to avoid the self-absorption and obtain high efficiency. Although the elementary processes of laser matter interaction can be investigated using molecular dynamics simulations, macroscopic behavior of the target is of the interest, for the optimization of the LPP EUV source. Therefore, we investigate a hydrodynamics model. We develop a model including transition from solid / liquid phase into gas / plasma phase of Sn, and model the stochastic structure formation such as bubble and cluster formation during the heating and evaporation as well as cooling and condensation processes in the laser produced plasmas.

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.

S32

Modeling of Target Deformations due to Pre-pulse with Debris Analysis

I. Yu. Vichev[1,3], V. G. Novikov[1,3], M. M. Basko[1,3], V. V. Ivanov[1,2], V. V. Medvedev[1,2]

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[2] *Institute of Spectroscopy RAS, Troitsk, 142090 Russia*
[3] *Keldysh Institute of Applied Mathematics RAS, Moscow, 125047 Russia*

Effective coupling of laser radiation to target is essential for the development of high-power sources of EUV and soft X-ray radiation that are based on laser-produced plasmas (LPP). This is especially important for LPP radiation sources employing so-called mass-limited targets, e.g. radiation sources for EUV lithography which make use of liquid tin droplet-like targets with typical diameter of few tens of micrometers. To improve the coupling of laser radiation to mass-limited targets laser 'pre-pulse' can be applied providing deformation of the target shape while some small fraction of the initial target being evaporated as a result of pre-pulse. To the moment various pre-pulse systems have been studied experimentally for the target engineering purposes [1]. Here we describe numerical model to describe the processes of deformation and fragmentation of liquid-tin droplets by laser pre-pulses. The model is based on the combination of RZLINE plasma code and OpenFOAM hydrodynamics code. The model is applied to study deformation of the target shape. We also analyze generation of fast micro-fragments caused by the pre-pulse action.

1. Hakaru Mizoguchi et al, LPP-EUV Light Source Development for High Volume Manufacturing Lithography, Proc. of SPIE Vol. 8679, 86790A.

Presenting Author

Ilya Vichev is currently a junior scientist researcher at the Keldysh Institute of Applied Mathematics of the Russian Academy of Science.

He completed his MSc in applied mathematics and physics at the Moscow Engineering Physics Institute (State University) in 2007, with a focus on modeling of the emission spectra of multi-charged ions in non-LTE plasma. His recent work is focused on modeling of the droplet morphology after the laser pre-pulse which is of interest in the development of EUV sources.

S33

Radiation Hydrodynamic Simulation of a High-brightness 13.5-nm EUV Microplasma

Hiroyuki Haya[1], Goki Arai[1], Takanori Miyazaki[1], Thanh-Hung Dinh[1], Takeshi Higashiguchi[1], and Atsushi Sunahara[2]

[1]*Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585 Japan*
[2]*Institute for Laser Technology, 2-6 Yamada-Oka, Suita, Osaka 565-0871 Japan*

We investigated the feasibility study of microplasma high-brightness EUV source at 13.5 nm as the metrology source. Metrology source as compared with the HVM has not yet converged to specific requirement, the light source needs to be stable, small with an etendue in the order of 0.03 mm^2sr, and high-brightness with a few watts of power. Microplasma for metrology source should be produced to be the order of 10-20 μm with a millijoule per pulse. We show two-dimensional radiation hydrodynamic simulations, which are supported by the experimental results. The distributions of the evaluated plasma parameters with the radiation term is calculated at a peak power density of 1×10^{11} W/cm^2, resulting in the EUV source size of 20 μm.

Presenting Author

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

S34

Plasma Source Modeling Accounting Non-LTE Radiation Transport and Level Kinetics In-line with Gasdynamics

D.A. Kim, V.G. Novikov, G.V. Dolgoleva, A.D. Solomyannaya

Keldysh Institute of Applied Mathematics RAS, Moscow, Russia

For computer modeling and detailed description of the processes in the target irradiated by laser pulse the model of non-stationary non-equilibrium plasma with account of level kinetics and radiation transport in spectral lines is constructed. Such model is based on the 1D Lagrangian RHD-code SND_RUSAM. The code allows carrying out simulation of the radiation and evolution of the plasma resulting from the impact of laser pulse. The self consistent solution allows to obtain the correct ionization stage of non-equilibrium plasma and accurate emission spectra. The calculations of plasma evolution, radiation spectra and conversion efficiency for different types of laser pulses are fulfilled. The comparison with results obtained using other approximations (LTE plasma approach and method using steady-state tables of non-LTE plasma properties) is presented.

Presenting Author

Dmitrii Kim is currently a junior scientist researcher at the Keldysh Institute of Applied Mathematics of the Russian Academy of Science.
He completed his MSc in applied mathematics and physics at the Moscow Engineering Physics Institute (State University) in 2007. Thesis was devoted to plasma modeling with account of detailed level kinetics.

His research interest is detailed level kinetics, gasdynamics and radiation transport in non-LTE plasma.

S35

Computer Simulation Tools for Plasma-based Sources of EUV Radiation

V.V. Medvedev[1,2], V.G. Novikov[1,3], V.V. Ivanov[1,2], I.Yu. Vichev[1,3], M.M. Basko[1,3], V.S. Konovalov[1,3], A.D. Solomyannaya[1,3], A.S. Grushin[1,3], , A.M. Yakunin[4], A. Bratchenia[4], D. Labetski[4], K. Feenstra[4] and K.N. Koshelev[1,2]

[1] RnD-ISAN/EUV Labs, Moscow, Troitsk, Russia
[2] Institute for Spectroscopy RAS, Moscow, Troitsk, Russia
[3] Keldysh Institute of Applied Mathematics RAS, Moscow, Russia
[4] ASML Netherlands, Veldhoven, The Netherlands.

Development of high performance EUV lithographic machines requires reliable and efficient simulations for design, optimization and troubleshooting purposes. The main challenge for such simulations is a correct description of various multi-physics processes that take place in plasma-based sources of EUV radiation and in UV-generated plasmas in source and optics compartments of EUV sources. Here we report on the development of the toolbox of software packages, dedicated to tackle the relevant EUV physics. That toolbox covers phenomena that are important for the development of LPP-based EUV sources and for the optimization of optics lifetime in the environment of EUV-generated plasmas:

- Hydrodynamics of deformation and fragmentation of liquid tin targets with laser pre-pulses;
- Radiative hydrodynamics of plasma driven by laser radiation;
- Expansion of the source plasma in gaseous atmosphere and optics contamination with the source-generated debris;
- Properties of radiation-generated plasma at optical surfaces.

Presenting Author

S36

Radiation hydrodynamics of tin targets for laser-plasma EUV sources

Basko et al

ISAN, Moscow, Russia

Presenting Author

In 1971 Mikhail M. Basko graduated with honors from the Moscow Institute of Physics and Technology, and in 1974 he received his PhD in theoretical astrophysics from the Institute for Space Research (Moscow, Academy of Sciences of the USSR). In astrophysics his work was focused on the theory of binary X-ray stars, accretion physics, and physics of radiation transport in cosmic surroundings. In 1979 he took a position of a senior researcher at the Institute for Theoretical and Experimental Physics (Moscow) and changed the field to the physics of inertial confinement fusion and high energy density in matter, where he received his habilitation (Doctor of Science) degree in 1996 from the Institute of High Temperatures (Moscow, Russian Academy of Sciences). Since 2012 he holds a position of a leading researcher at the Keldysh Institute of Applied Mathematics (Moscow) combined with a part-time professorship at the Moscow Engineering Physics Institute. M.M. Basko has published more than 100 research papers in scientific journals.

S37

Model for Plasma Debris Mitigation by Gaseous Atmosphere

V. Konovalov et al

ISAN, Moscow, Russia

Presenting Author

S39

Validation of EUV Source Models Against Experimental Simulations

A. Grushin et al

ISAN, Moscow, Russia

Presenting Author

S40

3D SIMULATION OF SHIFTED LASER PULSE COUPLING TO TIN TARGET

I. P. Tsygvintsev, A. Yu. Krukovskiy, V. G. Novikov

KIAM RAS, Moscow, Russia

The aim of this work is numerical simulation of physical processes taking place under the influence of the laser pulse on targets in order to obtain plasma that effectively radiates in a given spectral range. To simulate three-dimensional effects caused by misalignment of the laser pulse and the target three dimensional code 3DLINE is used.

Main approximation for describing laser plasma evolution is a model of non-stationary one-fluid two-temperature radiation gas dynamics. Radiation transport is calculated in multi-group diffusion approximation. Ray tracing algorithm is used for post processing of calculation results. Effects of non-equilibrium ionization, thermal conductivity, laser refraction and reflection are accounted in calculations. The equation of state and the optical data are used in a tabulated form from THERMOS library.

The impact of laser beam on the tin droplet target in the case when there is no axial symmetry (missed pulse) was simulated. Tin was used as target material due to its high efficiency as a source of extreme ultra-violet radiation for lithography. Calculation results are compared with data obtained using two-dimensional codes.

Presenting Author

S41

A New Setup for Observation of Forbidden Lines from Metastable Ions produced in Charge Exchange Collisions

Hajime Tanuma[A] , Naoki Numadate[B], Hirofumi Shimaya[A] , Nubuyuki Nakamura[C], Kunihiro Okada[B]

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In collisions of multiply charged ions with neutral gas targets, the charge exchange is one of dominant processes. Generally, highly excited states are produced in these collisions, and the photon emission is dominant decay path for the excited states. Therefore the charge exchange will be one of mechanisms of the EUV and soft X-ray light emissions from the high temperature plasmas. Nowadays, the charge exchange has been observed or proposed as the soft X-ray emission mechanism in many places of the space, namely, Earth's magnetosheath, heliosphere, super-nova remnant, and starburst galaxy. In these cases, strong contribution of the forbidden transition is suggested. However, the forbidden lines after the charge exchange collisions of multiply charged ions has not been observed by the ion beam experiment in laboratory yet. Typical lifetime of the metastable state which emit the forbidden line is about 1 ms. On the other hand, typical ion beam velocity is 100 - 1000 km/s. Therefore the typical flight length before the photon emission might be 0.1 - 1 km for the metastable ions. To observe the forbidden lines with long lifetime in a small laboratory, we had developed a Kingdon ion trap and just started a new challenge.

Presenting Author

Hajime Tanuma was born in Ibaraki, Japan on 10th March, 1962. He received his BS and PhD degrees in chemistry from Tohoku University. He joined Central Research Laboratory, Hitachi Ltd. in 1989. From 1989 to 1991, he involved in the development of cathode for high definition televisions He has moved to Department of Physics, Tokyo Metropolitan University as Assistant Professor in 1992, and had been promoted to Professor in 2013. Since he was a graduate student, he has investigated various kinds of ion collision experiments in the energy range from 0.5 MeV to sub-MeV.

S42

EUV Ablation of PPEES: Process and Critical Factors

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Preliminary investigation on short-wavelength ablation mechanisms of poly (1,4-phenylene ether ether-sulfone) - PPEES by extreme ultraviolet (EUV) radiation at 11.8 nm using a 10-Hz laser-plasma EUV source based on the double-stream gas-puff target irradiated with the 3-ns/0.8 J Nd:YAG laser pulse at WAT in Warsaw.
Polymer samples are irradiated in a focal plane of the EUV collector or at some distance downstream the focal plane.

Ablation of polymer materials is initiated by photo-induced polymer chain scissions. The ablation occurs due to forming volatile products by the EUV radiolysis removed as an ablation plume from the irradiated material into the vacuum. In general, a cross-linking of polymer molecules compete with the chain decomposition. Both processes may influence efficiency and quality of micro(nano)structuring in polymer materials.

Results are analyzed by means of scanning electron microscope and Raman spectroscopy. A detailed discussion on critical parameters of the process (i.e. wavelength and fluence) is presented. To analyze the limit of the ablation process, a comparison between these data and the ones obtained by EUV radiation at 13.5 nm by a table-top laser at LLG, in Göttingen and at 46.9nm by a 10-Hz capillary-discharge EUV laser at the Institute of Physics, in Prague is presented.

Presenting Author

Chiara Liberatore (Chieti, Italy, 01/01/1986) is a PhD student at Czech Technical University and a junior researcher at HiLase Center, Czech Republic. She received her B.S and M.S. degrees from University of Milano-Bicocca, Italy and has background on plasma physics.

S43

Quasi-Moseley's Law for UTA Spectra in High-Z Highly Ionized Charge States for High-power EUV & Soft X-ray Sources

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Bright narrow band emission observed in optically thin plasmas of high-*Z* elements in the extreme ultraviolet spectral region follows a quasi-Moseley's law. The wavelength varies from 13.5 nm to 4 nm as the atomic number ranging from 50 to 83. The range of emission wavelengths available from hot optically thin plasmas permits the development of bright laboratory-scale sources for applications including lithography, x-ray microscopy, and x-ray absorption fine structure (XAFS) determination.

Presenting Author

Yuhei Suzuki is a master course student in Utsunomiya University. His research activities have focused on efficient water window source for biological imaging and high conversion efficiency EUV source for HVM in next generation semiconductor lithography.

S44

Nanometer Optical Coherence Tomography using Broadband EUV light

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Optical coherence tomography (OCT) is a well-established method to retrieve three-dimensional, cross-sectional images of biological samples in a non-invasive way using near-infrared radiation. The axial resolution of OCT is on the order of the coherence length $l_c \propto \lambda_0^2/\Delta\lambda_{FWHM}$ which depends on the central wavelength λ_0 and the spectral width $\Delta\lambda_{FWHM}$ of a light source. As a consequence, the axial resolution only depends on the spectrum rather than the geometrical properties of the radiation. OCT with broadband visible and near-infrared sources typically reaches axial (depth) resolutions in the order of a few micrometers.

We present a novel method based on OCT for cross sectional imaging with nanometer axial resolution which is referred to as XUV coherence tomography (XCT). XCT uses extreme ultra violet light (XUV), e.g., from high harmonic generation (HHG), plasma, or synchrotron XUV-sources. In XCT, the coherence length of a few nanometers of broadband XUV sources is exploited. Thus, XCT extends OCT by improving the axial resolution from micrometers to nanometers. In a first step, we demonstrated XCT at synchrotron sources. Three dimensional images of nano-structured samples based on silicon and carbon were recorded. We reached an axial resolution of 12 nm in the silicon transmission window (30-99eV) and 3 nm in the water-window (270-530eV) – solely limited by the spectral transmission windows of the materials used. XCT with its capability to capture 3D images of silicon-based substrates non-destructively with an axial resolution of a few nanometer is a novel method to investigate semiconductors or lithographic masks actinically.

Presenting Author

S45

Coherent EUV Light Sources using Highly Efficient High Harmonic Generation

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[4] Queen’s University Belfast, United Kingdom

Extreme ultra-violet (XUV/EUV) light is needed for a wide range of applications such as lithography, nanoscopy, and medical diagnostics. Common light sources in this spectral regime are synchrotrons and plasma sources. Another promising method to generate coherent XUV radiation is the laser-based high harmonic generation (HHG) where a high-intensity femtosecond laser pulse is focused into a gas jet. The efficiency of HHG is usually lower than the one of plasma sources. On the other hand, the divergence is much smaller and the radiation is coherent. Therefore, the overall photon flux is comparable to that of XUV synchrotrons. However, the efficiency of HHG strongly depends on phase matching conditions in the laser focus.

We present a novel design for HHG, which overcomes the typical limitations of the efficiency for generating XUV light. With multiple gas jet systems we were able to compensate destructive phase effects for HHG and thus we could improve the conversion efficiency. We focused pulses from a table-top laser system (1 kHz, 10 mJ, 30 fs) into multiple gas jets containing neon and hydrogen to efficiently generate harmonic radiation from 13 to 30 nm. Prospectively, we want to use the generated radiation for the investigation of electron dynamics in atoms and molecules and for nanometer imaging techniques.

Presenting Author

S47

Laser Plasma Monochromatic Soft X-ray Source Using Nitrogen Gas Puff Target

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Laser plasma created in nitrogen gas puff target is studied as a source of monochromatic radiation with the wavelength of 2.88 nm. The wavelength corresponds to the quantum transition 1s2-1s2p of helium like nitrogen ion. The prevailing abundance of these ions is expected if nitrogen plasma is heated up to temperature 40 ~ 80 eV. Spatial developments of plasmas and its radiation characteristics induced by various laser pulses are simulated by 2D RMHD code Z* [1]. Namely, the results found for two different Nd:YAG laser pulses (600 mJ/7 ns) and (520 mJ/170 ps) with nitrogen gas at 1 bar pressure stimulated by experiments done in LLG are presented here. The evaluated duration of in-band radiation is 1.5 ns for 7 ns laser pulse, whereas it is 620 ps for 170 ps pulse. The energy of monochromatic radiation is ~25 times higher for 170 ps pulse. The computer results correspond properly to the laboratory experiments [2, 3]. Further computer simulations enable us to judge the effect of laser energy, pulse duration and wavelength on the spatial and time characteristics of this monochromatic SXR source.

[1] S.V. Zakharov et. al., in EUV Source for lithography, SPIE Press 2005, p. 223.
[2] K. Mann, et. al.: 2013 International Workshop on EUV and Soft X-Ray Sources,
http://www.euvlitho.com/2013/Proceedings%202013%20Source%20Workshop.pdf
[3] P. Vrba, et. al.: Physics of Plasmas 21, 073301 (2014).

Presenting Author

S48

Comparison of Laser Produced Plasma and Discharge Produced Plasma as a Source for Soft X-Ray Microscopy

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We compare two table top sources of extreme ultraviolet (XUV) radiation - laser produced plasma (LPP) and discharge produced plasma (DPP), with regard to cell imaging in the soft x- ray regime. Nitrogen plasma is ideal for monochromatic radiation with wavelength of 2.88 nm, which corresponds to the quantum transition $1s^2$-1s2p of helium like nitrogen ion. This wavelength is located in the water-window region, thus it provides the natural contrast between water and carbon-based substances, e.g. proteins. LPP source was developed in Laser-Laboratorium Göttingen e.V., Germany, plasma was generated by Q-switched Nd:YAG laser (1064 nm, 600 mJ, 7 ns pulse) focused into nitrogen gas-puff target. The typical photons flux was $6x10^{11}$ photons/(sr x line x pulse) for input nitrogen pressure p = 12 bar. The size of the plasma spot was 0.2 x 0.4 mm. DPP source was built in-house, plasma was generated by a current discharge through a 10 cm long, 3.2 mm inner diameter ceramic capillary filled with nitrogen gas. The charging voltage was 90 kV and the maximum current was 27.5 kA. Average photons flux was $5x10^{13}$ photons/(sr x line x pulse) and plasma spot had FWHM 0.3 mm. Thus, DPP has almost two orders higher photons flux than LPP, with appreciably longer duration of pulse.

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.

S49

Laser-Produced Plasma Spectroscopy of Medium to High-Z Elements in the 2 to 10 nm Spectral Region

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Spectroscopy of laser-produced plasmas (LPPs) of medium to high atomic number (Z) elements has been performed in the past and these elements are still being investigated as potential sources in the EUV spectral region. The region of the spectrum most commonly referred to as the "Water Window", between 2.3 and 4.4 nm, is of interest to those in the biomedical sciences due to its potential for high-contrast imaging based on the strong absorption by carbon and the low absorption by oxygen [1]. Sources that emit strongly at 6.X nm are also of interest for use in beyond extreme ultraviolet (BEUV) lithography in the semiconductor industry [2].

Plasmas were formed on a range of targets of medium to high Z number elements using an Nd:YAG laser. Illumination parameters, such as the power density, were varied to ensure a more comprehensive study of the spectral emissivity of these elements. Spectra were recorded using a 0.25-m grazing-incidence spectrograph, equipped with a flat-field, variable groove spacing grating with 1200 grooves/mm or 2400 grooves/mm, and a back-illuminated, TE cooled, CCD camera with 2048 pixels in the spectral direction.
Spectral analysis was carried out with the aid of Hartree-Fock with Configuration Interaction calculations using the Cowan suite of codes [3].

[1] P. A. C. Takman, H. Stollberg, G. A. Johansson, A. Holmberg, M. Lindblom, and H. M. Hertz, J. Microsc. 226, 175 (2007).
[2] G. O'Sullivan, T. Cummins, P. Dunne, A. Endo, P. Hayden, T. Higashiguchi, D. Kilbane, B. Li, C. O'Gorman, T. Otsuka, E. Sokell and N. Yugami, Phys. Scr. T156,014105 (2013).
[3] R. D. Cowan, The Theory of Atomic Structure and Spectra (University of California Press, Berkeley, CA, 1981).

Presenting Author

S50

Investigation of Laser-Produced Plasmas of Mo, Ru, Rh and Pd in the 2.4 nm to 13 nm Spectral Region

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The Rayleigh criterion resolution implies that the use of shorter wavelength radiation improves spatial resolution in photon based imaging and patterning systems. Over the past decade the development of sources at extreme ultraviolet and even shorter, soft X-ray wavelength is of a great interest for semiconductor patterning and cellular microscopy where high resolution is required. In the work presented here the spectra of laser plasmas of Mo,Ru, Rh and Pd in the spectral region from 2.4 nm to 13 nm, as potential new sources of radiation for these applications. The laser energy range covered by the experiments was from 623mJ to 5mJ. Spectral analysis of emission from different ion stages will be carried out with the aid of calculations for transition wavelengths and intensities using the atomic structure code of Cowan for the different ion stages identified and isoelectronic comparison with known Mo lines. [1]

[1] R. D. Cowan, The Theory of Atomic Structure and Spectra (University of California Press, Berkeley, CA, 1981).
[2] D. Colombant, G. F.Tonan-X-ray emission in laser-produced plasma, electron temperature

Presenting Author

Ragava is pursuing a joint PhD between Czech technical University and University College Dublin (Ireland) under Erasmus Mundus European Scholarship through EXTATIC. He obtained a Master of Science from Stockholm University, Sweden. He completed an internship at NXP, Nijmegen, on lead-free packaging, to assembly packages using lead free replacement materials and evaluate product quality both before and after reliability testing (MSL, TMCL and PPOT). Previously he had completed an Internship at IMEC, on one of the key issues of EUV lithography: EUV photo-resist out-gassing. He supported and demonstrated his proficiency in various domains in the field of optical lithography, provided high level of technical support and experience in operation, demonstration and installation of the EUV Lithography outgassing evaluation tool.

S51

Optimization of High Average Power FEL Beam for EUV Lithography Application

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[2]HiLase Center [3]Gigaphoton Inc.

Extreme Ultraviolet Lithography (EUVL) is entering into the high volume manufacturing (HVM) stage, after intensive research and development of various component technologies like Mo/Si high reflectivity mirror, chemically amplified resist, and especially high average power EUV source from laser produced plasma at 13.5nm. Semiconductor industry road map requires a realistic scaling of the source technology to 1kW average power, and further wavelength reduction to 6.7nm. It is recently recognized by the community of the necessity to evaluate an alternative approach based on high repetition rate FEL, to avoid a risk of the source power limit by the plasma based technology.It is discussed by several papers on the possibility to realize a high repetition rate (superconducting) FEL to generate a multiple kW 13.5nm light [1,2]. We must notice that the present SASE FEL pulse (typically 0.1mJ, 100fs, 1 mm diameter) has higher beam fluence than the resist ablation threshold [3], and high spatial coherence which results in speckle patterns in resist, and random longitudinal mode beat which leads to high peak power micro spikes.

A grazing incidence total reflection bended metal mirror is installed after the undulator to expand the beam area to reduce the beam fluence lower than the ablation threshold of resist. External-seeding configuration (HGHG) is employed to reduce the longitudinal mode beat, and beam homogenizer based on total reflection is used for spatial mode mixing. The pulse repetition rate is assumed more than 1MHz to cancel the speckle patter formation by averaging illumination, and to achieve kW average power. This paper discusses on the required technological assessment and lowest risk approach to construct a prototype based on superconducting linac and undulator, to demonstrate a high average power 13.5nm FEL equipped with mentioned optical components, for best optimization in EUVL application, including the scaling to 6.7nm wavelength.

[1] E.A. Schneidmiller, V.F. Vogel, H. Weise, and M.V. Yurkov, "A kilowatt-scale free electron laser driven by L-band superconducting linear accelerator operating in a burst mode", 2011 International Workshop on EUV and Soft X-ray Sources, November 7-9, 2011, Dublin, Ireland
[2] G. Stupakov and M. S. Zolotorev, "FEL oscillator for EUV lithography", SLAC-PUB 15900,January 2014
[3] J. Chalupský, L. Juha et.al, "Characteristics of focused soft X-ray free-electron laser beam determined by ablation of organic molecular solids", OPTICS EXPRESS **15,** 6036 (2007)

Presenting Author

S52

High efficiency 10 kW class FEL for EUV lithography

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Free electron laser (FEL) technology has reached the level of maturity, where the development of an industrial quality, high average power EUV FEL light source for lithography application is feasible. A 10 kW class machine can be constructed using the existing technological base, but the cost and reliability of the system scales favorably with the reduction of average electron beam current. Thus the FEL conversion efficiency is a critical optimization criterion in the machine design. We present the initial design study, summarizing the advantages and limitations of the FEL tapering and seeding techniques, in the context of the high power EUV FEL design and development.

Presenting Author

S53

Development of high repetition rate seed pulse at 324nm for EUV-FEL using picosecond thin disk regenerative amplifier

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High repetition rate FEL is considering as an alternative light source for EUL lithography. To realize the high repetition rate FEL for EUV light source, high average power UV pulse is required as a seed pulse of HGHG (high-gain harmonic-generation) process. We have proposed the HGHG FEL at 13.5-nm seeded by the UV pulse at the wavelength of 324-nm with the pulse duration shorter than 200-fs [1]. The estimated average powers of UV seed pulse for the 100-W and the 1-kW EUV-FEL are 20-W and 200-W, respectively. We are developing the UV seed pulse source using the high average power picosecond thin disk regenerative amplifier.

NIR femtosecond pulse generated from a mode-locked Yb-doped fiber laser is split into two pulses. One pulse is coupled into a photonic crystal fiber to generate a broadband MIR pulse. The other pulse is injected to the thin disk regenerative amplifier. The MIR pulse is amplified by OPA process pumped by the amplified IR pulse from the regenerative amplifier. We are also considering the amplification of the MIR pulse using a thin-disk-based Cr:YAG regenerative amplifier. The wavelength of amplified MIR pulse is converted to 324-nm by fourth harmonic generation. Details of the UV seed pulse source will be presented.

[1] A. Endo *et. al.*, “Optimization of high average power FEL beam for EUV lithography application”, FEL2014, FRA04 (2014).

Presenting Author

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

S54

The FERMI free electron laser soft – x-ray user facility

E. Allaria

FERMI commissioning team

FERMI is the seeded free electron laser operated by the Elettra – Sincrotrone Trieste laboratory in Italy as a user facility. With two seeded FEL lines using a single normal conducting linear accelerator, FERMI is producing high power and highly coherent radiation pulses in the spectral range going from 100 nm down to 4 nm with a maximum repetition rate of 50 Hz.

The commissioning of the first FEL line, which covers the wavelength ranges between 100 and 20 nm, started in 2010. After the commissioning period the FEL has been routinely operated for users since 2012.

The final optimization of the second FEL line, based on a double high gain harmonic generation stage cascade covering the wavelength range 20 to 4 nm has been recently completed and first user dedicated experiments will start in 2015.

We give an overview of facility and the typical operating modes of the FELs for users and we will report on the FERMI experience on critical aspects in operating short wavelength FELs.

Presenting Author

S55

Development of Superconducting Accelerator with ERL for EUV-FEL

Eiji Kako

KEK, High Energy Accelerator Research Organization, JAPAN

A feasible design of a superconducting accelerator for EUV-FEL was investigated. Superconducting cavities in CW operation are the most crucial key components for realizing the ERL (energy recovery linac) for EUV-FEL. The beam energies in a range of between 0.8 and 1.2 GeV and the average beam currents of 10 ~ 30 mA were considered in the required accelerator design [1]. The appropriate operating accelerating gradients, the required number of niobium 9-cell cavities, the optimum cavity structure, the specific design of CW cryo module, the supposed length of the main linac, the estimated capacity of large cryogenic system and the possible construction schedule in a very short term are carefully studied.

Construction of compact-ERL including superconducting cavity systems in both the injector and main linac was completed at KEK in 2013. The very stable beam operation at the beam energy of 20 MeV was successfully demonstrated [2], and the intensive effort to increase the beam power and beam quality has been continuously carried out. Infrastructures at KEK for cavity mass-production, cavity testing for qualification and module assembly are ready for construction of the ERL for EUV-FEL. In this talk, development status of the superconducting accelerator for EUV-FEL will be reported.

[1] R. Hajima, in this workshop.
[2] N. Nakamura et al., Proc. of IPAC2014, Dresden, Germany (2014).

Presenting Author

S56

Design of High-Power Free-Electron Lasers for EUV Lithography Applications

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Acceleration of high-brightness and high-power electron beams is becoming a mature technology thanks to development of energy-recovery linacs (ERL). High-power free-electron lasers (FEL) combined with ERLs have been constructed for wavelengths of infrared and recorded over 10-kW average power at Jefferson Laboratory. Since FEL wavelength is tunable by changing the electron energy, it is feasible to obtain a high-power radiation at a wavelength of EUV with a similar system to the IR FELs [1]. In this talk, we present a design of high-power EUV-FELs. The study is based on our up-to-date outcome from the ERL project in Japan, which is a collaborative framework of KEK, JAEA and other laboratories and universities. We present parameter sets for 10-30 kW FELs operated at 13.5 nm with considering technology readiness of critical components such as electron gun and superconducting accelerators. Results of FEL simulations are also presented to discuss the characteristics of EUV light from the FELs.

[1] R. Hajima et al., Sematech EUV Source Workshop, October 19, 2006, Barcelona, Spain.

Presenting Author

Dr. Ryoichi Hajima is an accelerator scientist. He is working on the developments of novel light sources based on high-energy electron accelerators, especially on energy-recovery linacs. From 1995 to 1998, he was an associate professor of University of Tokyo. Since 1999, he has been a staff scientist of Japan Atomic Energy Agency (JAEA). He is now Group Leader of gamma-ray NDA research group of JAEA and a visiting professor of KEK.

S57

Expectation and challenges of higher NA EUV lithography

Takayuki UCHIYAMA

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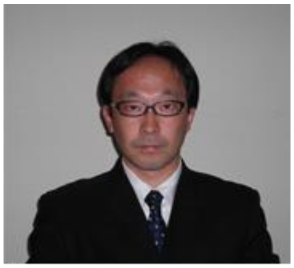
Multiple patterning requires very long process steps and very tight process control such as CD and overlay. EUV lithography is the most promising candidate of NGL (the next generation lithography). However, many difficult challenges must be overcome for practical use.

EUV source is the most critical issue. The target is 250 W in 2015 which corresponds to 125 WPH. However, the current power level of LPP source is still too low, less than half of the target. In the future, higher NA EUV lithography will require higher power due to resist shot noise issue for sub-10nm patterning. Furthermore, there is the trade-off issue of mask size and exposure field size and mask magnification for higher NA EUV lithography.

In this paper, the expectation and challenges of higher NA EUV lithography for sub-10nm patterning, including XFEL source as the source solution and etched multilayer mask as the solution for higher NA EUV trade-off will be mentioned.

Presenting Author



Takayuki UCHIYAMA is Chief Specialist of Lithography Process Technology Department, Center For Semiconductor Research & Development, TOSHIBA Corporation. He joined TOSHIBA Corporation in 2012 and has been involved in the research and development of the next generation lithography. He has 25 years of experience in lithography process development.

He received his B.E. and M.E. degrees in mechanical engineering from Tohoku University in 1987 and 1989, respectively. After graduation, he joined NEC Corporation, where his experience includes the production engineering of lithography process and the development of KrF, ArF and ArF immersion lithography. He has published numerous technical journal papers.

S58

Status, Perspectives, and Lessons from FLASH

E.A. Schneidmiller, M.V. Yurkov for FLASH Team DESY, Hamburg, Germany

Deutsches Elektronen Synchrotron (DESY), Hamburg, Germany

We will describe current status and plans of FLASH FEL user facility in Hamburg. Special attention will be devoted to experimental results related to the wavelength of interest of EUVL.

Presenting Author

Dr. Mikhail Yurkov is an expert in the field of physics of charged particle beams, accelerators, and free electron lasers. He has authored a book on free electron lasers and more than 180 papers in peer-reviewed journals.

S59

Optimization of a High Efficiency FEL Amplifier

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The problem of an efficiency increase of an FEL amplifier is now of great practical importance. Technique of undulator tapering in the post-saturation regime is used at the existing x-ray FELs LCLS and SACLA, and is planned for use at the European XFEL, Swiss FEL, and PAL XFEL. There are also discussions on the future of high peak and average power FELs for scientific and industrial applications. In this paper we perform detailed analysis of the tapering strategies for high power seeded FEL amplifiers. Application of similarity techniques allows us to derive universal law of the undulator tapering.

Presenting Author

S60

Accelerator technologies for EUV or Soft X-ray Lithography

Hironari Yamada

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In this talk he will summarize the present status of accelerator technologies useful to generate 1 kW monochromatic and coherent sources such as X-FEL, and ERL. Particularly Synchrotron-Cherenkov (SC) radiation which is not well known among lithography group will be introduced. This radiation mechanism was predicted in 1976, but until 2011 this radiation was not observed unless 20 MeV tabletop synchrotron was developed. This is a coherent radiation since Cherenkov, which is generated in dielectric materials, and is like SL because using kilo Gauss magnetic field. Despite 20 MeV low energy electron beam, whole radiations are focused into 5 mrd^2 solid angle. By one piece of 55 nm thick diamond like carbon (DLC) film nearly 100 mW of 277 eV radiation is generated. Since the focus size is 1x1 mm^2, particular optics can focuses all radiation into mm^2 restricted area. The 108 eV radiation can be generated by Be film. To generate 10KW radiation power combination of 20 MeV ERL and SC will be the optimum configuration for EUV or Soft X-ray lithography. Our tabletop synchrotron MIRRORCLE is actually the ERL.

Presenting Author

Hironari Yamada is a director of tabletop synchrotron light source center of Ritsumeikan University and a president of photon production laboratory Ltd.; an experienced scientist in the fields of accelerator physics, synchrotron radiation (SR) instrumentation, free-electron laser as well as nuclear structure physics. His one of the pioneering work is a development of the superconducting synchrotron light source (SL) AURORA for X-ray lithography. He is also the person who proposed for the first time a scheme to down size SR by introducing the laser Compton back scattering, Bremsstrahlung and transition radiation, and a photon storage ring FEL scheme with a circular mirror surrounding the electron orbit. He has successfully implemented such tabletop SR of 8 cm orbit radius, and established a company Photon Production Laboratory, Ltd. He is also working on many applications such as protein crystallography, EXAFS, SAXS, FIR spectroscopy and micron resolution CT. This CT system indeed provides the highest resolution 5 μm at very hard X-ray region. He is a 2007 science and technology prize winner given by the Japanese minister of science and education. His hobby is mountaineering as well as deep understanding of philosophical aspect of quantum mechanics in living phenomena. The title of recently published Japanese book is "Quantum mechanical approach to the meaning of existence, will and life".

S61

Possibility of High-*Z* Plasma Water Window Sources

Takanori Miyazaki, Yuhei Suzuki, Thanh Hung Dinh and Takeshi Higashiguchi

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We demonstrate EUV and soft x-ray sources in the 2 to 7 nm spectral region related to the beyond EUV (BEUV) question at 6.*x* nm and a water window source based on laser-produced high-*Z* plasmas. Resonance emission from multiply charged ions merges to produce intense unresolved transition arrays (UTAs), extending below the carbon K edge (4.37 nm). An outline of a microscope design for single-shot live cell imaging is proposed based on a high-*Z* plasma UTA source, coupled to x-ray optics. We will discuss the progress and *Z*-scaling of UTA emission spectra to achieve lab-scale table-top, efficient, high-brightness high-*Z* plasma EUV-soft x-ray sources with the soft x-ray microscope for *in vivo* bio-imaging applications.

Presenting Author

Takanori Miyazaki is a Ph.D. student in engineering at the Utsunomiya University. His research activities have focused on high brightness short-wavelength light source for soft x-ray microscope and atomic process in high-*Z* plasmas.

S62

Water-window Radiation from 40 kA Z-pinching Capillary Discharge Plasma

Michal Nevrkla and Alexandr Jančárek

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Z-pinching capillary discharge driver for investigation of nitrogen plasma as a possible active medium of XUV laser at 13.4 nm pumped by three-body recombination process was designed and tested. Nitrogen plasma generated by this source can serve also as a source of high intensity radiation at 2.88 nm. Introduction to the driver concept and output XUV radiation diagnostics are presented.

Presenting Author

Author is a Postdoc at FNSPE CTU. During Master and PhD studies author designed several capillary discharge drivers as EUV and XUV radiation sources. Currently continue his PhD research: Z-pinching capillary discharge driver for 13.4 nm laser.

S63

Soft X-ray Source for high speed soft x-ray tomography of cryo-frozen cells

Fergal O'Reilly, Kenneth Fahy, Padraig Dunne, Niall Kennedy, Paul Sheridan

School of Physics,UCD, Dublin, Ireland

Soft x-ray tomography bio-imaging at synchrotron facilities is changing the types of questions that biologists can ask by allowing them to see the organelle structure of unstained cells in a near-native cryo-frozen state[*]. We have developed a soft x-ray light source which has a radiance close to that of a synchrotron bending magnet in this region of the spectrum, and which uses simple plasma facing optics to protect laser optics and collect the soft x-ray photons to a clean intermediate focus. The source is powered by a commercial pulsed laser used in laser machining which makes it completely turnkey and relatively low cost. Here we report on recent source developments and future plans for deployment of this source to obtain full cell 3D tomographs.

[*]Journal of Structural Biology 162 (2008) 380-386

Presenting Author

S64

SOURCES FOR WATER WINDOW IMAGING

Gerry O'Sullivan[a], Padraig Dunne[a], Paddy Hayden[a], Bowen Li[ab], Ragava Lokasani[ac], Elaine Long[a], Hayato Ohashi[d], Fergal O'Reilly[a], John Sheil[a], Emma Sokell[a], Chihiro Suzuki[e], Elgiva White[a] and Takeshi Higashiguchi[f]
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Conventional sources for soft x-ray microscopy use H-like line emission from liquid nitrogen or carbon containing liquid jets which can be focused using zone plates. Recently the possibility of using MLMs with n=4-n=4 emission from a highly charged Bi plasma was proposed [1] and subsequently the possibility of using Δn=1 transitions in 2nd row transition elements was identified [2]. More recently we have investigated Δn=1 transitions in the lanthanides and 3rd row transition elements. All of these studies seek to identify spectral features that coincide with the reflectance characteristics of available MLMs and determine the conditions under which they are optimized. Thus there is a need for systematic studies of laser produced plasmas of a wide range of elements and some recent results on EUV spectral emission from a range of medium and high Z elements will be presented.

[1] T. Higashiguchi *et al*. Appl. Phys. Lett. **100**, 014103 (2012)
[2] B W Li *et al*. Appl. Phys. Lett, **102**, 041117 (2013).

Presenting Author

S65

3D characterization of chromatin structure

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[2]Department of Anatomy, University of California, San Francisco, USA
[3]Physical Biosciences Division, LBNL, Berkeley, USA

The three dimensional structural properties of the cell nucleus are related to cell differentiation and disease-induced alterations in nuclear physiology, e.g. virus infection, as well as in nuclear functions. Soft X-ray Tomography (SXT) can generate high-contrast 3D images of intact cells in a near native state with 50 nm resolution. In SXT we use photons with energies between the K-shell absorption edges of carbon (284 eV, λ=4.4 nm) and oxygen (543 eV, λ=2.3 nm), for which organic material absorbs an order of magnitude more X-rays than water. Cryofixed cells are imaged from multiple angles and reconstructed 3D images are those of the local linear attenuation coefficients (LAC). Because X-ray absorption follows Beer's Law, the local attenuation of photons is linear and a function of the biochemical composition at that point in the cell.

DNA viruses move to the nucleus due to their need for cellular DNA reproduction machinery in replication. Nuclear release of the viral DNA results in nuclear accumulation of viral proteins and replication of viral DNA leading to formation of viral replication compartments. Viral constituents disturb the spatial organization of the host cell chromatin and intranuclear protein distribution and dynamics. Upon herpes simplex virus 1 (HSV-1) infection the architecture of host cell chromatin is radically altered and expansion of the viral replication compartments (VRCs) is accompanied by chromatin marginalization to the vicinity of nuclear envelope. The organization and biophysical properties of chromatin and HSV-1 VRCs in infected cells are not well understood. Here, we provide novel soft x-ray tomography (SXT) insights into 3D distribution, compaction, and interconnection of chromatin and VRC in infected cells. Soft X-ray Tomography can provide novel understanding of the nuclear structure, which is expected to be useful in basic cell biology and in medical applications related to cancer research and viral infections. Creation of realistic model structures based on measured data can also be used to simulate transport properties of the nucleus.

Presenting Author

S71

LPP Light Source for Metrology and Inspection Applications

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

Extreme ultraviolet lithography (EUVL) is the leading candidate for the manifacturing of next generation semiconductor devices with node sizes below 10 nm. Laser-Produced Plasmas (LPPs) are one of the most promising sources for the EUV scanner. By irradiating microsized tin droplets with a high power (kW) lasers, plasmas emitting around 13.5 nm can be generated. LPP sources are promising also for metrology and inspection applications. For these applications lower power levels, but higher brightness and stability are required with respect to the high-volume manufacturing (HVM) lithography light sources. While inspection tools in the EUV are still under development, optical inspection tools operating in the DUV range are an established tecnology for wafer and mask inspection.


(a)

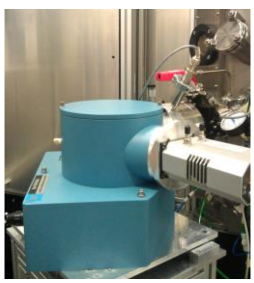
(b)

FIG. 1. (a) ALPS II facility with source chamber (right) and main controller (left), (b) VUV-spectroscopy tool.

At the Applied Laser Plasma Science (ALPS) laboratory of LEC-ETH Zürich, a droplet-based laser-produced plasma source with application in EUV high volume metrology has been developed. The main source ALPS II is today fully operational and is equipped with a large capacity droplet dispenser able to generate micrometer-sized droplets and a high power (1.6 kW), high repetition rate Nd:YAG laser. The source is equipped with several plasma diagnostics such as radiation detectors and spectrometers that allow to study the plasma emission proprieties from the EUV to the visible range. In this work, the emission proprieties of the LPP are investigated with a spectrograph operating in the Vacuum Ultraviolet (VUV) range with a 2400 Gr/mm grating at a spectral resolution of 0.06 nm. The emission spectra were recorded in a wavelength range from 30 nm to 550 nm for different fuels such as tin, indium and gallium in the presence of different background gases. These studies are relevant for alternative light sources that operate in the sub-80 nm range and help to determine the Out-Of-Band (OOB) radiation of the EUV source.

Presenting Author

S72

Femtosecond laser pre-pulse technology for LPP EUV source

Alexander Vinokhodov[1], Vladimir Krivtsun[1,2] , Mikhail Krivokorykov[1],Yury Sidelnikov[1,2],Sergey Chekalin[2],Victor Kompanets[2] , Alexey Melnikov[2]Konstantin Koshelev[1,2]

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[2] Institute for Spectroscopy RAS, Moscow, Russia

Results are reported for use of femto and picosecond laser in pre-pulse technology for LPP EUV source based on tin-indium alloy droplet target with diameters range from 40 to70 μm. Droplet deformation dynamics and ion flux measurements at laser pulse duration in band from 50 fs to 80 ps and laser power density up to $3*10^{15}$ W/cm^2 are studied by means of ultrafast shadow-graph method of visualization. Ion flux measurements carried out by Faraday cap and ion spectrometer. Droplets generated by annular piezoelectric actuator and had velocity up to 4 m/s at pulse repetition rate up to 5 kHz.

Presenting Author

S73

Evolution of the Energetiq Electrodeless Z-Pinch™source – What worked, and what didn't…

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

Energetiq Technology Inc., Woburn, MA, USA

Energetiq was founded in April 2004, with the goal of exploiting a newly conceived method for producing EUV radiation -- the Electrodeless Z-Pinch™. Within less than two months a prototype was operating, and we as a group began our still ongoing education in the art and science of producing and diagnosing EUV plasmas. We will report on some of our attempts to develop higher power and/or brightness sources, and the interplay of engineering and physics that led us to our current design.

Presenting Author

S81

Possible Beam Expander and Homogenizer for 13.5 nm Applications

Ladislav Pina

Czech Technical University in Prague

EUV lithography needs identified by semiconductor industry have stimulated development of optical systems to collect, collimate and focus radiation from relevant EUV sources. Several grazing incidence and Schwarzschild condenser optical systems were already developed and tested, as well as imaging systems. This topic can be further developed in the field of novel laboratory sources and ongoing research towards higher intensity. Presented material is a contribution to technical challenges of beam expanders and beam homogenization. Already existing experience with multi-foil optical systems and ray-tracing was used to study one of possible ways how to obtain expanded and homogenous beam of EUV radiation.

Presenting Author

S82

Multilayer Collector Mirror for DPP EUV Metrology Sources

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For many years laser-produced plasma sources use multilayer collector mirrors while grazing incidence collector mirrors are widely used for discharge-produced plasma sources. Multilayer collectors have different advantages compared to grazing incidence collectors:

- Homogeneous far-field image of plasma source,
- Spectral purity filtering of emitted EUV and non-EUV radiation,
- Easy thermal management by active or passive mirror backside cooling.

We present a multilayer collector mirror that has been developed and manufactured to focus EUV light emitted from a > 20 W/(2 π sr), 2 mJ/sr/pulse DPP EUV source to > 30 W/cm² average and >10^6.W/mm² peak intensity. We used an off-axis elliptical mirror for 1:1 imaging of the EUV plasma. The mirror has a diameter of 300 mm and was made of NiP plated Aluminum. The collector surface was polished to a roughness of less than 2 Angstroms rms and coated with a linearly graded Mo/Si multilayer. The paper presents the overall concept of the SoCoMo and the optical performance of the collector at 13.5 nm wavelength.

Presenting Author

S83

Spectral Purity Enhancement for the EUV Lithography Systems

Eric Louis[a,b], Qiushi Huang[a,b], Slava Medvedev[a,b], V. M. Krivtsun[c], Meint de Boer [a], Robbert van de Kruijs[a,b], and Fred Bijkerk[a,b]

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[b] *FOM Institute DIFFER - Dutch Institute for Fundamental Energy Research, P.O. Box 1207, 3430 BE, Nieuwegein, The Netherlands*
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Plasma based radiation sources optimized to emit 13.5 nm Extreme UV radiation also produce a significant amount of light at longer wavelengths. This so called out-of-band (OoB) radiation is detrimental for the imaging capabilities of an EUV lithographic imaging system, particularly the ultraviolet (UV) parts of the light (λ=100-400 nm). If the plasma is a produced by a focused CO_2 laser (=10.6 μ), scattered laser radiation will also contribute to the detrimental effects as well as to unwanted heat load on the resist.

Apart from filtering, two multilayer integrated methods exist to suppress these longer wavelengths. One is based on hybrid multilayer systems that are designed to simultaneously reflect EUV light and act as an anti-reflection coating for the longer wavelengths. The other method is based on diffraction, both from grating like structures as from more exotic features like pyramids integrated in the multilayers.

Proofs of principle of both methods are produced and will be shown. For the UV range of 100-400 nm a suppression factor of 14 was obtained, while the EUV reflectance reduced by only 4%.The IR light could be suppressed 70x at the expense of only 8% EUV reflectance.

Presenting Author

S84

Controlling Interface Chemistry in 6 nm La/B Multilayer Optics

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For future photolithography processes, the wavelength of 6 nm can be considered. The perspective of this chip fabrication technique however, will depend on the possible performance of multilayer reflective mirrors, which will need to be based on La/B. One of the issues is formation of La_xB_y compounds at the interfaces, which decreases the optical contrast and therefore dramatically reduces the reflectivity. To prevent such chemical interaction, passivation of La by nitrogen has been investigated. We successfully synthesized LaN layers that resulted in a new world record reflectivity of 64% at 6.6 nm at near normal incidence. This reduces the gap to the target of 70% desired for a possible next generation lithography.

Presenting Author

S85

Damage to optics under irradiations with the intense EUV FEL pulses

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The properties of an intense Free Electron Laser beam create, apart from new technological opportunities, extreme demands to optics such as Mo/Si multilayers. The radiation load imposed on optical elements for beam diagnostics, controlling and shaping can lead to their damage. It has been shown that optical coatings are destroyed by single FEL pulses if the beam's intensity exceeds a critical level, the single shot damage threshold. At such a fluence the temperature of the material reaches the phase transition point. Secondly, for high repetition sources, like required in lithographic applications, the heat load on optics may reach the kW level. This will lead to optics heating and its destruction, e.g. due to the enhanced atomic diffusivity in Mo/Si multilayers. Furthermore, repeatable irradiations of optics may cause multiple shot damage, e.g. related to thermal stresses. Moreover a rapid deposition of the EUV pulse energy at the optics surface can cause its hydrodynamical deformations resulting in wavefront distortions for the proceeding pulses. Last but not least, the combination of high photon flux with high photon energy may cause surface contamination with hydrocarbons, similarly to what is observed at synchrotron radiation sources.

Presenting Author

S91

Source radiance requirements for high-resolution imaging and interference techniques

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The focus of this presentation is set on the determination of the necessary EUV-source parameters for modern high-resolution imaging and interference lithography techniques. These parameters are given in terms of radiance and are determined using fundamental considerations of the achievable sample resolution, image contrast, detector sensitivity and required throughput. Besides application to the traditional EUV and soft-x-ray microscopy, the described method has been used also for determination of the source requirements for modern coherent microscopy and coherent nanostructuring. For latter, understanding the physical processes governing the requirements of the illumination sources is of high importance. For example, in the coherent diffractive imaging method, images are reconstructed from diffraction patterns. Thus, it is crucial for unambiguous reconstruction of nano-objects to illuminate these with radiation optimized for producing detailed speckle-reach diffraction patterns. For the interference lithography, in which the mask (or reticle) is an effective diffraction grating, the parameters of the illuminating radiation influence spatial resolution and quality of nano-structuring. In this talk examples of experimental realization of the mentioned techniques using compact EUV sources are demonstrated and methods to determine source requirements for different applications are described.

S92

Characteristics of soft x-ray emission from optically thin high-*Z* plasmas in Large Helical Device

Hayato Ohashi[1], Takeshi Higashiguchi[2], Yuhei Suzuki[2], Goki Arai[2], Bowen Li[3], Padraig Dunne[4], Gerry O'Sullivan[4], Hiroyuki A. Sakaue[5], Daiji Kato[5], Izumi Murakami[5], Naoki Tamura[5], Shigeru Sudo[5], Fumihiro Koike[6], and Chihiro Suzuki[5]

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Characteristics of soft x-ray emissions were investigated with optically thin high-Z plasmas in the Large Helical Device (LHD). Comparing with the optically thicker laser-produced plasmas, different spectral structure was observed due to the difference in optical thickness and electron temperatures. Calculations using the atomic code identified peak structures on unresolved transition arrays (UTAs). The main contributions of discrete line emission are from Pd-, Ag-, and Rh-like ion stages.

Presenting Author

Hayato Ohashi is an assistant professor. He received his Ph.D. in physics from Tokyo Metropolitan University. His research activities have focused on emission spectroscopy of multiply charged ions in ion-atom/electron collisions and laser-produced plasmas, and pulsed power system.

EUV

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