2016 Source Workshop Summary

Vivek Bakshi, EUV Litho, Inc.

(Workshop Summary are notes taken by the author during the workshop. Please point out any errors or omissions to the author.)
Status Update
Overlay and Focus requirements are challenging in advanced Litho (1-2 nm overlay and 50-40 nm focus). Pellicles are needed. 80% availability, 1200 WPD (NXE3350B), 1488 WPD in lab. Currently 8 systems in field.

Comparison of single exposure with MP 193i: optical and electrical 125 W at customers, 210 W dose controlled in lab (6% CE). For higher power /reliability need to increase in CE, Laser power, transmission and decrease overhead (dose control).

>100 Hours droplet generator runtime
>100 Gp collector lifetime

Roadmap until 500 W for this Sn LPP technology.
Workshop Summary

9:00 AM...Session 1: Keynote Presentations
X-ray Microscopy with Laboratory Sources (S2)
Hans M Hertz, KTH/Albanova, Sweden

Water-window x-ray microscopy

**Historical Efforts by the group:**
1990 - First Liquid-droplet Laser-plasma slide
1993 First liquid droplet EUV Source – H₂O (O VII 13 nm)
1999 First ML condenser optics
2003: 2.5% CE from Sn droplets

Liquid N₂ jet gave the least amount of debris for LPP
Present: 200W laser 600ps 2kHz gives early synchrotron level of brightness

3D tomography with 10 s exposure
>4% reflectivity (optiXfab) @ water window
Workshop Summary

10:35...............Session 2: HVM EUV Sources I

Development of 250 W LPP EUV Light Source for HVM Lithography (S11) (Invited) Georg Soumagne, Gigaphoton
Pilot #1 System - 250 W target (production version)
CO2 Laser - Shift from Fast axial flow to Fast transverse flow
5.5 % CE
100 W @ 5% CE, 95 % duty cycle for 5 hrs, 9.1 kW laser power, 50 kHz
Workshop Summary

10:35.............Session 2: HVM EUV Sources I
Correlation of Fundamental Plasma Parameters with EUV Emission Profiles of Sn LPP (S12) (Invited), Kentaro Tomita, Kyushu University

Optimum: $Ne = 10^{24-25} \text{m}^{-3}$, $Te = 30-50 \text{eV}$, $Z = 8-13$

Laser Thompson Scattering for Ne and Te (time resolved)

Adequate $Ne > 5 \times 10^{24}$ and $Te > 30 \text{ eV}$ were achieved for optimum CE

Time distance between pre and main pulse is important and there is an optimum delay time
Workshop Summary

10:35............Session 2: HVM EUV Sources I

Power Scaling of Pico-second Thin Disc Laser for LPP and FEL EUV Sources (S13) (Invited) Akira Endo, HiLASE

Additional Applications: ERL (energy recovery Linac) FEL for >kW 13.5 nm EUV source

Temporal smoothing of FEL pulses by UV ps laser seeded HGHG

Single shot bio-imaging by laser Compton X-ray-source

Requirements for beam quality ($M^2$) for spot size and focus length

Specs:

4 mJ at 100 K Hz, >0.5 kW in CW mode

1.4kW at 1 MHz demonstrated

ps, >mJ pulse energy, 100 K Hz, >100 W laser available for prepulse in LPP sources
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Dynamics of a Metallic Micro-droplet upon Interaction with Nanosecond Laser Pulse (S14) (Invited) D. Kurilovich, ARCNL

Plasma propulsion of microdroplets driven by laser pre-pulse: Propulsion leads to deformation – scalability of hydrodynamic stability of droplets

Equation of motion derived from experimental data:
\[ F_{th} \sim 2.4 \text{ J/cm}^2 \text{ (Theoretically } 5 \text{ J/cm}^2) \]

Verified scalability of hydrodynamic response from H2O to Sn droplet
Workshop Summary

1:00 PM ..........Session 3: HVM EUV Sources II
High-radiance LDP Source: Clean, Reliable and Stable EUV Source for Mask Inspection (S15) (Invited)
Yusuke Teramoto, Ushio Inc.
Radiance behind debris shield: 145 W/mm² sr
No damage or Sn deposition on collector after 24 hours
Energy stability <10% (pulse),<0.2% dose
10 days non-interruption operation 100 W/mm² for 5 days
15 kHz , 70 W/mm² sr operation demonstrated
At IF 10 W (1.5 W in-band)
Workshop Summary

1:00 PM ..........Session 3: HVM EUV Sources II
Droplet-based High Brightness LPP Light Sources for High Volume Metrology and Inspection Applications (S16) (Invited) Reza S. Abhari, ETHZ

Long term operation of 14 hours, 6-20 K Hz operation, at maximum power with no measured debris at the collector (GI collector) -

<table>
<thead>
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<th>Parameters</th>
<th>Value</th>
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<tr>
<td>Laser power on target (W)</td>
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<tr>
<td>Laser frequency (kHz)</td>
<td>&gt;6</td>
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<tr>
<td>Laser focal spot - FWHM (μm)</td>
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<td>Conversion efficiency (%)</td>
<td>&gt;1%</td>
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<td>Source power at the source (W)</td>
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<td>Source brightness (W/mm²sr)</td>
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Workshop Summary

Scaling of Discharge based XUV Sources for Metrology Applications (S17) (Invited) Klaus Bergmann, Fraunhofer – ILT

Simpler design of discharge based sources (as compared to LPP)
Development results for various Xe,Kr and N2 Hollow cathode discharge sources

Source Specs
6.7 nm ----Kr---- 13 mJ/mm² sr
13.5 nm ---Xe--- 52 mJ/mm² sr nm
2.88 nm --- N2--- 2.5*10⁷ Ph/(µm² sr)
A High-Brightness LPP EUV Source based on Liquid Lithium Jet for Actinic Mask Inspection (S18) (Invited)

Samir Ellwi, ISTEQ

Self cleaning laser entry window and EUV output window (heated to 540 C) for Lithium
Self enclosed Li system – not in contact with EUV optics
1000 hours life for Li re-circulating system for current system
(10 K Hours expected after upgrade)

Expected source performance:
2.5 % CE
1 kW mm²/sr brightness
Collectable in-band power at IF - 60 mw
Workshop Summary

Progress Towards Actinic Patterned Mask Inspection (S19) (Invited)
Oleg Khodykin, KLA-Tencor

Current non-actinic system for >=10 nm nodes
Sensitivity limited by edge roughness
Presence of pellicles means we need EUV (193 nm transmission too low) for inspection of patterned masks
All vacuum suppliers have challenges with contamination

Requirements:
20 W/mm².sr, >10 ns pulse length

Performance: 120 Hours, 80% DC, >8W/mm²sr @5 KHz, no reflector degradation at 5 kHz operation (5000 Hours)

Path to 40 W/mm²sr
Maximize line emission by reducing opacity and reducing recombination.

“Density has a sweet spot”

To optimize CE:

*Wedged target colliding plasma better matched to CO2*

Indicates that with optimum control of pre-pulse conditions *CE>5% is possible*
Workshop Summary

2:50 PM Session 4: Plasma Dynamics
Physics of Laser Ablation and the Quest for Maximum CE (S22) (Invited) M. M. Basko, KIAM and RnD-ISAN/EUV Labs

Spectral purity (SP) of EUV emission from Sn plasmas
SP degradation due to self-absorption in-band
Maximum thermal possible CE ~ 20% (from Nishihara’s 2008 paper showing 40% spectral efficiency)
Density Ni<=10E18 Ne <=10E19 cm^-3
Temperature 30-40 eV, optical thickness 10-30%

1. Via preparation of density profile – maximum CE 11.5 % in transient peak
2.5% lost as the kinetic energy of plasma flow. Rest due to non-uniformity of T across the “working” zone and in-band reabsorption

2. Via self-consistent ablation density profile max. CE 9% in steady state
Loss due to self-absorption and non-uniformity of temperature
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2:50 PM Session 4: Plasma Dynamics
Cross-sections for Electron-impact Ionization of Tin ions from a Crossed-beams Experiment (S23) (Invited)
Stefan Schippers, University Giessen

Absolute Electron ion collision cross section for Sn $^{4+}$ to Sn$^{13+}$
Consistency set of ionization rate-coefficients for tin ions
Uncertainty from presence of metastables?

Working on High energy High density electron gun 3.5keV – to explore new regions
Workshop Summary

Charge-state Resolving Analysis of EUV Spectra using Electron-beam Ion Traps (S24) (Invited)
José R. Crespo López-Urrutia, Max-Planck-Institut

EBIT- ions in any desired charge state can be prepared, stored and spectroscopically studied

Even most advanced theoretical methods are not as accurate as the experiments
Charge state and electronic state resolving studies are needed to guide theory
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Electron and Ion Dynamics in EUV-induced Plasmas (S25) (Invited) J. Beckers, Eindhoven Univ. of Technology

EUV and background H2 interaction in the chamber forms electrons, ions, molecular radicals like H3+

**MCRS**

Compared dynamics of Ar and H2 dynamics in the chamber and found them to be similar with following key differences:

Max. electron density more than an order higher in the case of argon
- \( \rightarrow \) cross section
- Plasma expansion and decay much faster in hydrogen
- \( \rightarrow \) ion mass
- Chemistry in H\(_2\) plasma. E.g. formation of H\(_3^+\)
Workshop Summary

8:50 AM ..................................Session 6: Keynote -2
Interferometry, Spectroscopy and Lensless Imaging with Extreme-ultraviolet Radiation (S3)
Stefan Witte, ARCNL and VU University

Interesting properties of EUV Radiation: Diffraction from nanoscale objects, element selectivity, high photon energy provides access to core levels

Coherent EUV Source development (OPCPA)

Applications Overview: XUV Spectroscopy and EUV Interferometry, HHG FT spectroscopy, Lensless CDI, HHG Wavefront measurements
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9:30 AM ..........................Session 7: XUV Applications
Coherent Diffraction Imaging with Partially-coherent Discharge Plasma based EUV Sources (S71) (Invited)
Larissa Juschkin, RWTH Aachen University

CDI and Ptychography examples

**Ptychography with LDP: 100 nm resolution – 50 nm possible**

**Application for detecting phase defects in ML, actinic inspection of ML, acquisition of phase information of nano particles**
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9:30 AM .......................... Session 7: XUV Applications
Transient XUV and X-ray lasers pumped by Free Electron Laser Sources (S72) (Invited)
Nina Rohringer, Max Planck Institute

Fundamental study of XUV lasing
Photoionization lasing scheme in XUV domain – Auger-decay

XFELs open the door to study x-ray and XUV stimulated emission

Auger-pumped XUV lasing schemes revisited
Optimization of Laser-produced Plasma towards the Generation of High-order Harmonics (S74)

N. Smijesh, Griffith University

Motivation: Increase the energy cut-off for HHG

Study of Hydrodynamics of LPP via imaging – for generating HHG
Fiber laser plus nonlinear compression for table top XUV sources

Fiber lasers with Sub 30 fs pulses and 400 W average power for HHG generation

10E9 Ph/s up to 150 eV (into water window region) \( \sim 10 \text{ MHz} \)

1mW at 21.7 eV (2.5 \( 10^{14} \) ph/s) – commercial table top source

XUV microscope: 12 nm resolution
Plasmonic HHG

Shown recently that HHG from solids is possible
Possible applications for the EUV fluorescence from waveguides (10E? Ph/s)
High degree of control via tailored local intensities and polarizations
Chemical composition can likewise influence harmonic generation

Mapping of structural, electronic and chemical dynamics in solids with nanometer spatial and attosecond time resolution in a transient fashion

Together with sensitivity to internal fields:
  Comprehensive insight into operating semiconductor integrated circuits
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Applications of a Table-top Laser Driven EUV/Soft X-ray Source and Wavefront Optimization at Short Wavelengths (S43) (Invited) K. Mann, Laser-Laboratorium Göttingen

XUV Sources and Schwarzschild Objectives for EUV damage studies

NEXAFS (Kr Plasma for water window) - For probing X-ray absorption edges for various elements and applications

Soft X-ray microscope at 2.88 nm
Brilliance improvement by going to ps lasers from ns lasers
Planned projects with HiLase on ps lasers

Wavefront measurements at FEL at 13.5 nm
Unresolved Transition Array (UTA) Emission from Highly-charged Ions in Heavy-element Plasmas by a Dual-laser Pulse Irradiation (S44) (Invited) Takeshi Higashiguchi, Utsunomiya Univ.

Experimental of verification of Quasi-Moseley’s law
3-20 ns variable pulse system based on CO2 laser
Goal of a single shot flash source in WW for bio imaging

Increased spectral intensity from dual pulse irradiation

220 mJ per pulse energy at Bi target

27.4 % reflectivity ML at 4 nm (Cr/Sc/Mo 10 Trilayer)
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Laser-produced Highly-ionized Aluminum Plasma for High Harmonic Generation (S46)
Reji Philip, Raman Research Institute, Bangalore, India

7 ns laser pulses 20 - 85 mJ pulses, YAG Laser

Characterised the Al plasma for HHG generation

Stark width for estimation of Ne
In vacuo-LEIS is used for monitoring thin film growth and closed layer determination for Ru on Si, SiN and SiO$_2$, and Si on Ru

Study of MLM structure after deposition using XRR and XSW

Comparison of reconstructed profiles for two deposited LaN/B-based multilayers reveals differences in compound formation on LaN-on-B interface

Model for blisters have been build for the prediction of trends in blister formation
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**Leading Edge EUV /XUV Optics – Enhanced ML for WW (S52)**  
(Invited) Torsten Feigal, optiXfab

\[ R = 70.12\% \text{ at } 13.48 \text{ nm} \]
\[ R = 18.22 \text{ at } 2.422 \]
\[ R(\text{average}) = 3.66\% \text{ at } 2.478 \text{ nm} \]

*Changed distribution of reflectivity on mirror*

\[ R = 4.58\% \text{ at } 2.478 \text{ nm Cr/V with barriers} \]

*(reduced scan time for tomography from 20 mins to 2 mins)*

\[ R = 26.22\% \text{ at } 2.738 \text{ nm} \]

\[ R = 8-10 \% \text{ possible for } 2.88 \text{ nm (Modeling)} \]
A Study of EUV/SXR Grazing Incidence Collectors for Metrology Sources (S53) (Invited)
Ladislav Pina, Czech Technical University, Prague

Expert in replication technology – replicate GI mirrors

Review of various applications in the industry
(First LPP image taken in 1985 in Warsaw using GI mirror)
R= 50 % for GI mirror for WW

Replicated GI Mirrors Spectral and Focusing Characterization
Commissioning of the European XFEL has started
Post-saturation undulator tapering demonstrated increase of the radiation pulse energies above 1 mJ.
Harmonic lasing in the high gain SASE FEL has been demonstrated experimentally for the first time.
**Significant increase in the spectral brightness and Coherence time (2x)**
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3:00 PM........................ Session 10: FEL based Sources
Strategy to Realize the EUV-FEL High-power Light Source
(S62) (Invited) Hiroshi Kawata, KEK

Presented prototype design of EUV –FEL
25 x 150 design will require double loop or high gradient –
which means very high utility consumption

In order to keep the technology node trend of computer chip
makers, it is important to push forward the construction of
the prototype EUV-FEL light. (Need 1 kW in 2024)

To this end, source group, tool and material venders, and end users
should have collaborative works from the early stage.

Planned EUV-FEL meeting in December
3:00 PM........................ Session 10: FEL based Sources

Linear and Non-linear Interaction of X-ray Free Electron Laser Radiation with Materials (S63) (Invited)

Hermann A. Dürr, SLAC, USA

$10^{13}$ Ph/pulse at 120 Hz - single shot magnetic holography possible

At high fluence, speckle pattern disappears

Linear and non-linear x-ray interaction with materials

Non-linear interaction explains resonant magnetic scattering

Stimulated resonated scattered photons are correlated
4:15 PM.............................................Session 11: Modeling
Multiphysics Model of Plasma Interaction with Gas flow
in EUV Source chamber (S31) (Invited)
D. Astakhov, RnD-ISAN

3D transient model that couples energy and momentum input from
tin plasma to the flow in the EUV source chamber

Listed relevant time and space scales hierarchy

The model can be used to optimize the chamber geometry, flow
structure etc. for regime during source operation
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4:15 PM..............................................Session 11: Modeling
How a Laser Impact Propels, Deforms and Fragments a Liquid Drop: The Liquid Dynamics of the Pre-pulse (S32) (Invited)
Hanneke Gelderblom, Univ. of Twente

“Water drops as scale model for tin”
Questions to answer: How to shape a drop? How does the drop deform? How and when drops fragment?
Dynamic properties of fluids have similar behavior – weber number = Kinetic Energy /surface energy
Drop extension – water and tin collapse into similar curves
Faster expansion by decreasing focal spot size
Can adjust parameters (R/Ro vs We) to work in regions to avoid drop breakups! Can stay fully intact but do not expand much.
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4:15 PM..............................Session 11: Modeling
Simulating EUV Generation in Laser-Produced Plasma (S33) (Invited) Howard Scott, LLNL, USA

LLNL codes are being applied to EUV production
Complex code, developed for laser fusion has been modified for 1 μ and 10 μ laser wavelengths

Including microphysics of EUV generation
laser absorption, NLTE kinetics, hydrodynamics, radiation transport, conduction
Aiming to resolve length / time / frequency scales and minimize uncontrolled approximations
Applying to laboratory experiments to aid the experimental diagnostics

UCD experiments with multiple diagnostics to validate the code
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Application of Plasma Formation Modeling for LPP EUV Sources (S34) (Invited) Igor Fomenkov, ASML

Overview of modeling efforts
Scan parameters that are experimentally not accessible
Pre-pulse modeling using HYDRA- discovering the physics critical to pre-pulse simulation accuracy
Simulated Spectra were improved using NLTE
Visualize laser interaction and local EUV generation within puffed Sn droplet
CE, Simulated EUV Spectra, shadowgram
Connecting with power scaling
Announcements
Publication of Workshop Proceedings

Please email me a PDF version of your presentation at Vivek.bakshi@euvlitho.com, if you have not already done so.

You are welcome to change your presentation for publication in the proceedings.

Deadline for submissions of revised presentation is Tuesday, November 16, 2016.
2017 International Workshop on EUV Lithography
(2017 EUVL Workshop)

June 12-15, 2017, The Center for X-ray Optics (CXRO), Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Upcoming Workshops

www.euvlitho.com

2017 International Workshop on EUV and Soft X-Ray Sources
(2017 Source Workshop)

November 6-8, 2017, Dublin, Ireland
Thank you!

- I will like to thank following for making 2016 Source Workshop a success!
  - Workshop Sponsors – Financial support
  - Source Technical Working Group (TWG) - Guidance
  - Session Chairs and Presenters
  - Joris Scheers, Francesco Torretti – running computers
  - Oscar Versolato (Co-Chair), Joost Frenken, Marjan Fretz for organization of agenda /logistics
  - Special thanks to Romy Metz and Rosa Andrea of ARCNL for excellent organization and hard work!