Workshop Summary

Vivek Bakshi

Meeting notes. Please inform me of any inaccuracy.

Workshop summary is also published at my blog at http://electroiq.com/euvl-focus/

UCD DUBLIN

EUV LITHO, INC.

www.euvlitho.com

Workshop Agenda
Tuesday, November 4, 2014

9:00 AM Session 1: Keynote-1

EUVL for HVM: Progress and Risks (S1)

Mark Phillips, *Intel Corporation*

Four sources operating at customer sites at > 40 W (for normalized collector lifetime)

One source operating at 80W (55 WPH)

Source power roadmap is regaining credibility

Reasonable improvement in collector lifetime

3300B is able to work in the production environment

All specs are met except productivity (availability)

Source availability is <40% (average) due to droplet generator

HVM usage is dependent on source power, availability and OpEx – (capex contribution to wafer cost)

Infrastructure challenges: Actinic inspection needed (Source related)

Working to demonstrate that actinic inspection will be needed

Scaling of free-standing pSi film demonstrated (50 nm free standing membranes are now routinely shipped)

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One Hundred Watt Class EUV Source Development for HVM Lithography (S2) Hakaru Mizoguchi, *Gigaphoton Inc.*

Only 2% transmission with 11 mirrors resulting in the need of 250 W for HVM
Stability of droplet of +/- 20 microns achieved
Ps pre-pulse improves CE to>4.5% and increases Sn ionization
20 kW CO_2 drive laser operational
45% collector reflectivity and improved collector cleaning to 31.6% cleaning (plasma to IF)?
42 W, 50% duty cycle, 21 W average for 3 Hours (110 M pulses)
60 K Hz, 70% duty cycle, 10 minutes -83 W average power (118 W clean power) for 20K pulses, 3.7 %CE, 10.2 kW CO_2 laser

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10:35 AM Session 2: HVM EUV Sources

EUV Lithography: Towards Industrialization (S29) (Invited)

Wim van der Zande, *ASML*

Multi-patterning drives need for EUV

>500 wafers exposed per day during tests at 2 sites

40 W at four customer sites (42, 57, 52, 52 W)

Stable source power over 2 months from customer site (IBM)

80 W at 24 hours at one customer site

List of topics for further source research:

- **Improved automation algorithms**
- **In-situ collector cleaning towards a dynamic equilibrium**
- **Using hydrogen gas for stopping ions and cleaning collector**
- **Increasing reliability of the droplet generator**

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10:35 AM Session 2: HVM EUV Sources

Nishamura (Osaka University)

It is not yet clarified yet why CE is substantially increased due to pre-pulse–optimized plasma or increase in laser absorption

Simulation shows 6-8 % CE for double pulse 10 ns (due to increase in laser absorption)

Experiment shows correlation between laser absorption and CE

30-49 eV temperature ion density E18 cm-3 Z ~ 10.

6-8 % can be achieved. Lack of number of radiators achieved by increasing droplet frequency

Bob Rollinger (EHTZ)

Current milestones of debris mitigated EUV collector and cleanliness have been met for Lasertech

3 layer debris mitigation strategy (plasma site, collector and IF)

validation of tin-based LPP source after IF for cleanliness

Pulse to pulse stability of EUV energy at 3%

10 x reduction in debris via adjustment of debris mitigating gas flow

6 KHz operation, 50 micron droplets

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Femtosecond Laser Pre-pulse Technology for LPP EUV Sources (S72)

Alexander Vinokhodov, *EUV Labs/RnD ISAN, Russia*

Use Sn-In alloy for convenience (70% CE as compared to pure tin)

High energy ions (upto 8 keV) fly only in the opposite direction to the direction of the propagation of laser beam

There is a minimum of high energy ions at 800 fs

Ion multiplicity at 50 fs > 400 fs

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

Stephen F. Horne, *Energetiq Technology Inc.*

Inductive plasma source

Collection efficiency of EUV sources

To improve the brightness – considered adding magnetic field along Z-axis – need 100-200 G to affect pinch behavior

Power doubled and operating pressure lowered

10% increase in brightness

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Source Requirements for Next Generation AIMS EUV (Invited) (S94)

Udo Dinger, *Carl Zeiss, Germany*

If pellicle is used- final actinic inspection is required!

>100 W/mm2/sr target with 30 acceptable

<3% FWHM position stability

<3.5 % energy stability

Metrology Source Requirements for KLA Actinic Inspection Tool (Invited) (S93)

Oleg Khodykin, *KLA-Tencor*

Teron 710-APMI Specs:(3-4 hours for entire mask inspection)

>10 K Hz, **> 20 W/mm2.sr source brightness**,pulse >10 ns, etendue 1E-2mm^2.sr, Cost of service<10%, Cost of operation<5%

Metrology Source Requirements for Actinic Mask Blank Inspection (Invited) (S95) Lasertech

(presented by Stephen F. Horne, Energetiq)

Etendue 0.02 mm^{2}sr.Brightness >30W/mm^{2}sr, 10 ms integrated stability <1%, 14 days continuous operation.

Period maintenance < 6 hours

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1:45 PM Session 3: Modeling

Computer Simulation Tools for Plasma-based Sources of EUV Radiation (Invited) (S35)

V. V. Medvedev, *ISAN and Institute for Spectroscopy RAS*

Rayleigh-taylor instability causes generation of particles, that are expunged from the edges of the droplet

More higher energy ions and energy is directed back towards laser

How to validate target ablation rate?

Ion spectra and charge distribution – biggest cause of uncertainty in the model

Hydrodynamics Modeling of the Dynamics of Sn Droplet Target for the EUV Sources (S31) Akira Sasaki, *Japan Atomic Energy Agency, Japan*

Modeling methods to simulate mist formation by irradiating droplet by prepulse are investigated.

Test calculations for expansion of heated tin are carried out, which shows evaporation of liquid tin and cluster formation of tin vapor during expansion.

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2:45 PM Session 4: FEL-1

Expectation and Challenges of Higher NA EUV Lithography (Invited) (S57)
Takayuki UCHIYAMA, *TOSHIBA Corporation*
Concerns for high NA EUVL---resolution and throughput trade-off, high power source (6x proposal from ASML?), tougher optics requirements and potential optics damage
High NA EUV trade off –EUV Optics
Etched ML pattern for high NA, enabler for 4x high NA EUV (IMEC showed simulations at 2014 EUVL Symposium)
List of concerns for FEL: Proof of concept, availability, cost and timely readiness (5 years)
Energy Recovery Linac will reduce electric power consumption of FEL
High power may damage optics in high power FEL
Coherence needs to be managed

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2:45 PM Session 4: FEL-1

Optimization of High Average Power FEL Beam for EUV Lithography Application (Invited) (S51) Akira Endo*, Waseda University and HiLase SASE FEL*

List of potential challenges:

Ablation threshold < resist sensitivity

Need to reduce spatial coherence, homogenizer will be needed

Need for low roughness optics

100 fs pulse length of FEL compared to 10 ns from LPP

Need temporal smoothing

Foot print of LPP architecture becomes similar to FEL at kW level (scaling limit of LPP is around kW)

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2:45 PM Session 4: FEL-1

High efficiency 10 kW class FEL for EUV Lithography (Invited) (S52) Alex Murokh, *RadiaBeam Technologies*

Proposal for SASE FEL *(borrowed from Alex's presentation)*
LCLS-II is a gateway to industrial XFELs with demonstrated commercial components

10 kW industrial EUV FEL can be developed with minimal risk using the existing technological base:

- High Brightness CW Injector
  - APEX photo injector under construction for LCLS-II
  - DC Gun-Cornell (shown 80 mA average current)
- CW SCRF cryo modules are under construction at Fermilab and JLAB for the LCLS-II
- Hybrid permanent magnet technology for undulators is mature (kilometers has been built)
- Accelerator design: XFEL physics and beam dynamics are well understood, supported by high fidelity numerical tools, and validated

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2:45 PM Session 4: FEL-1

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

Eiji Kako, *High Energy Accelerator Research Organization*

EUV light source by using ERL is technically available in power levels around 10 kW, presently.

Infrastructures for construction of prototype ERL for EUV/FEL is ready at KEK, and the realistic construction schedule of the prototype ERL for EUV/FEL was shown.

First EUV light could be possible in 2019, if the R&D is started just now.

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4:05 PM Break /Group Photograph (20 Minutes)
Accelerator Technologies for EUV or Soft X-ray Lithography (S60) (Invited – Review Talk)

Hironari Yamada, *Ritsumeikan University, Japan*

100 mW generated via 20 MeV tabletop synchrotron (11 nm)

(1K multiplexing has potential to provide 1 kW)

Compact system

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EUV source Candidates (from S60)

Radiation mechanism	Accele-rator	Ee	Size	Focal point size	Power		COST (MUS$)	comments
					Ave.	Etendue/ mrad^2		
undulator	storage ring insertion	>1 GeV	30m Dia.	20μm dia.	10 mW	25W	30	1KW is not achievable
SASE FEL for X-ray	Normal C Linac	>1 GeV	1km long	100 μm dia.	1J/ pulse	100J/ pulse	300	Average power is low
SASE FEL for EUV but not for soft X	ERL with Super C LINAC	>300 MeV	>20m long	1mm dia.	10 KW	10 KW	300	Feasible but many to be studied
SCR or TR for EUV and soft X	Storage ring	<20 MeV	1mx3m	10μm x 1mm	1 KW	10 KW	5	Existing
	ERL with Normal C		5mx5m		10 kW	1000 KW	10	Feasible but many to be studied

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The FERMI Free Electron Laser Soft – x-ray user Facility (S54) (Invited)

E. Allaria , *FERMI commissioning team*

Seeding has shown to improve also FEL energy stability.

HGHG FEL energy stability at the level of few % is demonstrated, but generally stability remains critically dependent on the stability of other subsystems (beam energy, electron orbit, seed laser ...).

Operation of single stage HGHG at 13 nm has been demonstrated.

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

Ryoichi Hajima, *JAEA and High Energy Accelerator Research Organization, Japan*

ENERGY RECOVERY LINAC (ERL) are not storage rings

Proposal for a high power EUV FEL was first made in 2006

Development of 500k V DC gun completed

12 nm FEL for12 kW, saturation length of ERL (55m)

0.145 mJ x 81.25 MHz = 12 kW

800MEV, 8 mA ERL can produce 10 kW EUV

130 m length LINAC

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

M. V. Yurkov, DESY, Germany

- **Both, burst and cw options allows to construct high average power (multi-kW) SASE FEL as a source for the next generation lithography. 10 kW level.**

- The main concern of the future developments of high power systems is reliable prediction of the electron beam properties and the **problem of beam halo seems to be an issue.**

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Tomographic Imaging with Soft X-rays (S3)
Carolyn Larabell, *UC San Francisco*

Advantages: Look at whole cell in its native state
Zone plate lenses – diffractive optics
Example of development of malaria infected red blood cell
Study of genes
Blood cell differentiation
Changes in chromatin and nuclear volume
Cryo confocal tomography
Correlated Fluorescence and X-ray Tomography

Brief Presentation (5 minutes) –UCD Physics Overview (S99)
Padraig Dunne*, UCD*

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9:25 AM Session 8: Optics
Multilayer Collector Mirror for DPP Sources (S82) (Invited)
Torsten Feigl, *optiX fab GmbH*

Multilayers for 4.3 nm – R 11.3%
At 13.5 nm R =70.12% at 13.49 nm
Beam splitters for 13.5 nm (R =20% and transmission 21.5 %)
Narrowband multilayers for 30-38 nm
Primary mirror for space research
Ni coated Al mirrors for EUV

Possible Beam Expander and Homogenizer for 13.5 nm applications (S81) (Invited) Ladislav Pina, *CTU Prague*
Overview of soft-ray optics
Comparison of FEL and LPP sources
Potential Optics schemes for FEL
Requirements: Suppression of diffraction and speckles, optics for quasi parallel beam, small beam size and submicron size at IF etc.

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9:25 AM Session 8: Optics

Spectral Purity Enhancement for the EUV Lithography Systems (S83) (Invited)

Eric Louis, *University of Twente and DIFFER*

ML based solutions for IR filtering (with reduced EUV reflectivity)

250 x suppression of IR at 45% EUV reflectivity

Grating based suppression better for higher EUV reflectivity

Re-usage of removed IR

DUV antireflective coating

Blazed diffraction + interference+ absorption UV

Optics lifetime issue?

Damage to Optics under Irradiations with the Intense EUV FEL Pulses (S85) (Invited)

Ryszard Sobierajski, *Polish Academy of Sciences*

Characteristics time scales and related processes

Models for Atomic diffusion in Mo/Si ML (13.5 nm) – compaction and crystallites formation (Single shot)

Heat diffusion by phonons and heat accumulation

Heat accumulation - melting

What happens from multiple pulses? Fluence?

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11:10 AM Session 9: Soft X-ray Sources and Applications

A New Setup for Observation of Forbidden Lines from Metastable Ions produced in Charge Exchange Collisions (S41) Hajime Tanuma, *Tokyo Metropolitan University*

EBIT

Kingdom Ion trap for observation of forbidden lines

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

C. Liberatore, *HiLASE and Czech Technical Univ.*

PMMA to study EUV ablation

Double stream gas puff target based source

Chemical properties of the materials are minimal

Conditions for EUV ablation : Non- monochromatic source

(Important topic for EUV outgassing for material selection)

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

M. Wünsche, *Friedrich Schiller University and Helmholtz Institute*

Potential of HHG sources for EUV

μ to mW – not useful for lithography

May be used as seed for FEL?

XUV Coherence tomography

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

M. Vrbova, *Czech Technical University*

7 ns, 450 mJ, or 170 ps 380 mJ pulse (Nd:Yag laser)

Modeling of 2.876 to 2.886 nm region – good match with experiments on

Absorbed and emitted power

SXR energy and brightness vs target density

Imaging and time resolved luminescence spectroscopy

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

Larissa Juschkin, *RWTH Aachen University*

Examples

Water window microscopy and Pump and probe EUV Microscope

Contrast

Sensitivity index

Source radiance requirements (proportional to $1/\lambda^{3}$)

Laboratory-scale lens less EUV imaging

EUV Interference Lithography

Talbot lithography technique (15 nm L/S)

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1:50 PM Session 10: Water Window Microscopy

Sources for Water Window Imaging (S64) (Invited Review Talk) Gerry O'Sullivan *(University College Dublin)*
Physics of UTA, Origin of "UTA" name and description
Properties and applications
Optimum source for water window matching MLM still needs to be identified
Atomic data are essential for source identification
Need for spectral wavelength and intensity data for various elements

Water window radiation from 40 kA Z-pinching capillary discharge plasma (S62)
Michal Nevrkla, Czech Technical University
Source FWHM 280 μm, 12 mJ/sr at 2.88 nm, 770 nJ

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3D Characterization of Chromatin Structure (S65) (Invited)
M Myllys, *University of Jyväskylä, Finland*
Measure LAC, volume, surface areas and structural properties of one whole cell
Measurement at several angle to get 3D tomographs
Can provide noval understanding of the nuclear structure, to understand the basic cell biology (Source requirements: within 1 square Angstron, 1000 Photons in 1 sec)
Will pay 750 k- 7 M range for a microscope

Soft X-ray Source for High-speed Soft X-ray Tomography of Cryo-frozen Cells (S63) Fergal O'Reilly, *University College Dublin*
To bring synchrotron techniques to lab
Microscopy requirements - need small and bright sources
Solved plasma debris issue and debris for laser window
CE for Mo based target -- 0.16 % in water window
Plasma diameter 18 microns

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Thank you!

- Thanks for making 2014 International Workshop on EUV and Soft X-ray Sources a very productive workshop! Special thanks to:
  - Workshop Sponsors
  - EUVL Workshop Steering Committee
  - Session Chairs
  - Presenters
  - Padraig Dunne (Co-chair)
  - Isaac Tobin (Trinity for running the computer)
  - **UCD Physics Office Staff (Stephanie, Barbara, Magdalena)**
- **Hope to see you again in 2015!**


2015 International Workshop on EUV Lithography
Makena Beach & Golf Resort, Maui, Hawaii
June 15-19, 2015


2015 International Workshop
on EUV and Soft X-Ray Sources
Dublin, Ireland
November 9-12, 2015