2016 EUVL Workshop
Workshop Summary

Vivek Bakshi

EUV Litho, Inc.

June 16, 2016

(Workshop Summary are notes taken by the author during the workshop. Please point out any errors or omissions to the author.)

Workshop Summary: June 15 2016

- **EUV Lithography's Present and Future (P1)**
- Harry J. Levinson, *GLOBALFOUDRIES*
- ***Early 2014 to today big progress---75% uptime + 80 W***
  - You can do a lot of development with 200 Wafers per day
- **Learning during development vs R&D are different**
  - **For Example – contamination during reticle handling**
- **Not reasonable to expect 250 W with >90% within few years**
  - Cost comparison with LELELE at 250 W
- **9 additional masks means ~ 2weeks of cycle time**
- **Areas where works is left to be done:**
  - **Yield, process control, OPC, low defect mask blanks**
  - Higher NILS, process control for EUVL (new way to find the best focus, tight control requirements for CD and overlay,)
  - Resist capability - LER improvement
- **We are now looking into insertion of EUVL in few years**
  - **2018-2019 insertion and need FEL few years after that**

EUV Litho, Inc.

Workshop Summary: June 15 2016

- **EVUL Readiness for High Volume Manufacturing (P3)** Britt Turkot, *Intel*
- Source power progress with dose control
- **Droplet generator – 5 x improvement in run time demonstrated** will result in significant improvement in system availability
- **Focus needs to remain on system availability**
- Scanner defectivity is decreasing but not fast enough and not to zero, hence, pellicle is required
  - Key improvement – flow around new stages and flush out particles
- NXE3300 – 14 nm pilot line – demo completed – combined availability meets expectations
- **Pellicles learnings – no reticle adder observed in wafer prints, particles on pellicles do not mitigate to reticle surface, pellicle frame design is mitigating adder issue**
- Did not see change in pellicle transmission and uniformity (700 wafer run). Need to improve pellicle defects and increase thermal load handling
- Availability of quality pellicle membranes in high risk
- Complicated process to mitigate defects – need to reduce blank defects
- Patching and cutting repair via E-beam
- High photospeed – some contacts may not print at all (7 sigma fluctuations) due to shot noise
- **Many important fundamental questions on EUV resists**
- Highly desirable at 7 nm node but will be used when ready
- Long way to go but making progress – Availability, opEx, pellicles

Workshop Summary: June 15 2016

- **<u>Development of 250 W EUV Light Source For HVM Lithography (P34)</u> (Invited)**
- H. Mizoguchi, *Gigaphoton*
- 64% market segment in DUV sector
- 250 W system configuration (27 kW laser, >75% availability)
- Droplet generator lifetime 260 hours at 40 Mpa
- CO_2 laser profile proved -will improve CE
- **5.5% CE observed via pre-pulse optimization**
- **188 W for 7 Hour (Apr 2016), 100 K Hz, 50% DC, 30% dose margin**
  - **In open loop > 200 W observed**
- **119 Hours of 158-132 W in closed loop and stable operation**
- **Goal of 250 W by December 2016**
- **5% CE, 40 kW, 100 K Hz for 500 W system proposal**

EUV Litho, Inc.

Workshop Summary: June 15 2016

- **CO_2 Amplifiers to Generate > 20 kW Laser Power for Stable > 250 W Extreme Ultraviolet (EUV) Power (P33)** **(Invited)** Koji Yasui, *Mitsubishi Electric*
  - **Provide CO_2 amplifier (>25 kW) for 250 W source**
  - 400 kW input gives 27 kW output power at 100% duty cycle
  - ***For >500 W source, need >40 kW of CO_2 paper***
  - ***For 1K W source, >60 kW of CO_2 laser*** *– need to change design of laser oscillators (Input of 800 kW)*

EUV Litho, Inc.

Workshop Summary: June 15 2016

- **<u>New Concepts for a High Brightness LPP EUV Source (P35)</u>** Samir Ellwi, *ISTEQ*
- 400 $W/mm^2 sr$ at 8 K HZ drive laser rep rate, power density 1.8x 10^{11} W/cm^2, CE 2.3%
  - High position stability and mass uniformity σ x/y of 0.5.0.8 μ
  - **2kW $W/mm^2 sr$ observed**
- **Li droplet based system – enclosed, > 1kW $mm^2 sr$, 1kW brightness, 10 K Hz, 2-4$10^{-5}$ mm^2 sr etendue**
- **List of potential advantages – stability, lifetime**
- **200 W lifetime limit due to Li pump is to be extended**
- **<u>Laboratory Soft X-ray Tomography with a Simple Robust Laser Plasma Light Source (P32)</u> (Invited)**
- P. Dunne, *University College Dublin*
- Application of 13.5 nm source technology developed for water window application
- **6 months to get back to 13.5 nm with the new and improved source technology in water window**

Workshop Summary: June 15 2016

- **1:00 PM .... Session 3: FEL based EUV Sources**
- **Free-electron Lasers: Beyond EUV Lithography Insertion (P41) (Invited)** Erik R. Hosler, *GLOBALFOUNDRIES*
- Exploring the FEL application space
  - **N3 needs 500 to 1000 W in 2024. FEL is a candidate**
  - **More acceptance now from chipmakers on FEL than 3 years ago**
  - **To avoid optics damage, will need to switch to GI optics for cooling**

High Efficiency Free Electron Lasers (P44) (Invited)

- Alex Murokh, RadiaBeam
- **Industrial EUV FEL is a source of excitement, but also a challenge for the FEL community**
- **An alternative to ERL is to look into possible improvements to FEL efficiency.**
- **TESSA (Inverse FEL) – proof of concept experiment was successful. Demo of 30% efficiency at 10.5 μm Need to follow up at shorter wavelength**

Workshop Summary: June 15 2016

- **1:00 PM ………… Session 3: FEL based EUV Sources**
- **Design and Development of a 10-kW Class EUV-FEL Project in Japan (P43) (Invited)** Ryukou Kato, *KEK*
- **Development of compact ERL**
  Energy of 20 MeV, 1 mA electron beam is successfully recovered
  Small beam loss operation is achieved

- **Performance of the designed EUV-FEL (modeling results)**
  12.1 / 24.2 kW output obtained at 9.75 / 19.5 mA with tapering
  Energy recovery after 12 kW lasing seems to be possible

- EUV-FEL Study Group for Industrialization is established
  10 companies, 1 consortia, 7 Universities, Research Laboratories

Workshop Summary: June 15 2016

- **2:30 PM Session 4: EUV Optics**
- **EUV Lithography High-NA Scanner for Sub 8 nm Resolution (P61) (Invited)** Jan van Schoot, *ASML*
- Larger NA reduces local CDU
- New anamorphic concept results in the half filed image
- **New stage technology can allow 185 WPH**
- **Identified ways to meet tighter focus requirements**

Workshop Summary: June 15 2016

- **2:30 PM Session 4: EUV Optics**
- **Multilayer coatings for the First Micro-Exposure Tools with NA=0.5 (P64) (Invited)**
- Regina Soufli, *LLNL*
- *Overview of ML manufacturing at LLNL*
- Velocity modulation is used during deposition to produce ML with precise thickness control
- **Achieved 0.1 nm rms contribution to wavefront error for M1 and M2**
- Developed Mo/Si multilayer coatings with -100 MPa stress and 60% reflectivity.
- **Achieved multilayer-added figure errors < 80 picometers rms over 250 mm clear apertures**

Workshop Summary: June 15 2016

- **2:30 PM Session 4: EUV Optics**
- **<u>Atomic-scale Investigations of Formation and Aging Processes of EUV Optics (P66)</u> (Invited)**
- Joost W.M. Frenken, *ARCNL*
- **STM movies of interface roughness and erosion of surface to collect statistics and study fundamentals**
- **Observations on Ion smoothing of deposited Mo**
  - Removal rate is proportional to the damage already done
  - Perfect Si(111)-7×7 is almost perfectly reflective for 800 eV Ar^+ at 75°

Workshop Summary: June 15 2016

- **<u>Diffractive Optics for EUV Applications (P67)</u>**
- Ryan Miyakawa, CXRO
- **Overview of zone plates applications**
- **Phase material can increase ZP efficiency**

Workshop Summary: June 15 2016

- **<u>Fabrication of EUVL Micro-field Exposure Tools with 0.5 NA (P68)</u>** Luc Girard, *Zygo Corporation*
- *Mirror fabrication results – achieved flare 2.75 % (Spec 5%)*
- **Performance better than specs:**
  - The achieved single pass transmitted wavefront of 0.21 to 0.24nm RMS is less than half of the 0.5nm specification at the center of the field.
  - The maximum measured single pass transmitted wavefront across the specified field is 0.48nm RMS, less than the 1.0nm specification.
- The MSFR and HSFR are well in spec.
- The average achieved flare of 2.75% is close to half of the 5% specification

EUV Litho, Inc.

Workshop Summary: June 15 2016

- **Multilayer EUV Optics with Integrated IR Suppression Gratings (P69)** Torsten Feigl, *optiX fab GmbH*
- *R= 70.12% at 13.48 nm, FWHM 3.86 nm, AOI 30 degree for Mo/Si ML*
- *Pros and Cons of multilayer structuring and substrate structuring*
- *ML structuring for YAG wavelength (Ru cap did not cover the open ML on sidewalls)*
- ***Substrate structuring – grating wall not smooth but no open ML and one can put a cap layer. This can avoid blistering***
- ***Binary phase grating to remove 10 μ and 1 μ laser wavelengths***
- ***R=64.24% IR suppression factor of 260 (10 μ) and 620 (1μ)***

Workshop Summary: June 16 2016

- **<u>EUVL Exposure Tools for HVM: Status and Outlook (P2)</u>**
  Igor Fomenkov, *ASML*
- Announced acquisition of Hermes Microvision
- *405K wafers exposed at customer sites, 85 WPH on NXE3350B*
- ***Three customers have 80% availability at 80 W config.***
- *3300 B are exposing >1000 WPD at multiple sites*
- *125 W at IF with 20% overhead, mean pulse energy 3 mJ*
- ***210 W does controlled demonstrated at ASML (5.5 % CE, 20 kW CO2, 10% overhead)***
- **3400 MOPA+PP -- 5.5 % CE (partial cloud) , 6% CE demonstrated on development platforms (cloud target)**
- **Pellicle has been proven up to 125 W source power**
- SPIE 2016, 97760K-1, Michael Purvis, Advances in predictive plasma formation modeiling
- **Droplet at 16 microns and meet stability requirements**
- **Collector lifetime 3 months, 80 GP, 1000 Hours droplet generator**
- 250 W feasibility w/o increasing H2 flow for collector protection
- 8 NXE3300 B operation at sites

EUV Litho, Inc.

Workshop Summary: June 16 2016

- **Session 6: Mask-1**
- **<u>Eigenmode Analysis of Electromagnetic Fields in Binary EUV Masks (P51)</u>** Michael Yeung, *Fastlitho*
- ***Vertical propagation of lowest Eigenmodes in an isolated 4-nm space reduces shadowing and non-telecentricity effects, this allowing use of thicker absorber layers***
- **Absorber thickness needs to be used carefully to utilize this effect**
- **<u>Challenges for Predictive EUV Mask Modeling (P82)</u> (Invited)** P. Evanschitzky, *Fraunhofer IISB*
- **Challenges related to EUV mask simulation** & product review
  - Thick absorber layer with oblique illumination
  - Larger simulation area with respect to wavelength
  - Multilayer is prone to defects
- **Simulation of pellicle with tilt and particles, can evaluate effect of non-uniformity and thermal load**

Workshop Summary: June 16 2016

- **Session 7: Mask -2**
- **Actinic Mask Inspection System Using Coherent Scattreometry Microscope (P84) (Invited)**H. Kinoshita, *University of Hyogo*
- **HHG source – 1 μW, 0.17 mrad, 13.5 nm 59th harmonics**
- **Signal for 2 nm high defect, 10 s exposure**
- CSM can detect 24 nm wide absorber defect
- Small phase defect with high res at 25 nm can be detected using micro- CSM

Workshop Summary: June 16 2016

- **Session 7: Mask -2**
- **<u>Near Wavelength Limited, 15nm Spatial Resolution, Ptychographic Imaging using a 13.5nm Tabletop High Harmonic Light Source (P59)</u> (Invited)**
- Henry Kapteyn, KMLabs Inc.
- Synchrotron vs HHG
- **CDI - Most photon efficient imaging**
- CDI amplitude image enables imaging of elemental composition - Seeing through buried layers and interface
- Next steps --- >20 W average power, optimized HHG scheme (optimized XUUS), improve resolution to sub-10 nm
- **XUUS – 1 to 200 k Hz operation –** commercially available with M2~1

Workshop Summary: June 16 2016

- **Session 7: Mask -2**
- **<u>Improvement of Coherent Scattering Microscopy by Applying Ptychographical Iterative Engine (P55)</u>**
- Dong Gon Woo, *Hanyang University*
- Accuracy of probe function is the key of resolution of reconstructed image. Hence, correction of probe function error is required
- *Limited by small field of view so we applied PIE*
- ***Beam instability and position accuracy can be improved by PIE***
- **Tolerance of position accuracy could be relieved from 1% to 15% of step size**

Workshop Summary: June 16 2016

- **12:50 PM Session 8: Mask -3**
- **<u>Extreme Ultraviolet Mask Manufacturing: Challenges and Opportunities (P52)</u> (Invited)**
- Bryan Kasprowicz, *Photronics Inc.*
- *Tightening Mask Process requirements*
- *Black border and EUV DUV requirements*
- ***Effort to reduce from 5 % to < 2% OOB reflection***
- *55 nm optimal absorber thickness (and new materials) for best process conditions*
- *Dual resist strategy to manage multiple mask layer types*
  - NCAR process performance has improved resolution and LER performance, but at the expense of write time

Workshop Summary: June 16 2016

- **12:50 PM Session 8: Mask -3**
- **Progress and Opportunities in EUV Mask Development (P53) (Invited)** Ted Liang, Intel
- DUV inspection of trench/via – marginal performance in HVM
- EBMI inspection capability results
- **Actinic inspection – source readiness remains a high risk**
  - >30 W/mm2 for 2 hr TPT
  - >40 W/mm2 for post –pell inspection (85% single pass transmission)
  - Position stability <10 μm
  - Possible to make an inspection tool based on met sources available
- Pellicle status –
- **Requirements - >250 W, 0.4% transmission non-uniformity, >90% transmission Innovative materials are needed**
- **Delivering defect free masks for 7 nm development**
- **Challenges – Pellicle integration and Actinic inspection**

EUV Litho, Inc.

Workshop Summary: June 16 2016

- **Eureka (P85) (Invited)** Patrick Naulleau, *CXRO*
- ***Review of tools and capabilities***
  - Reflectometer, 0.3 NA , SHARP - AIMS, 0.5 NA
  - Characterization of EUV radiation chemistry
  - RSoXS: Soft X-ray potential for 3D chemically sensitive profile metrology

Extending CO_2 Cryogenic Aerosol Cleaning for EUV Mask (P57) (Invited), Ivin Varghese, *Eco-Snow Systems, RAVE N.P. Inc.*

- Requirements: Removal of all soft defects, zero damage to mask, no lifetime reduction for masks
- Demonstrated cleaning of 37 nm SRAFs
- Front and back side cleaning
- Co2 Cryogenic Aerosol cleaning
- **100% removal of all post repair printable defects**
- **No damage to Ru, change in CD or reflectivity after 50 x.**
- **Cannot removal chemical contamination**

Workshop Summary: June 16 2016

- **2:30 PM Session 9: Resist -1**
- **<u>EUV Radiation Chemistry Fundamentals: Novel Probing Techniques (P72)</u>** Oleg Kostko, *LBL*

- ***Processes after EUV photon Absorption – four steps***
  - *Photoionization, Electronic relaxation, Atomic relaxation, inelastic scattering*
  - *First two via photoelectron spectroscopy and second two via mass spec*

- *Able to probe:*
  - Energies and yield of electrons, emitted after EUV photon absorption
  - Fragmentation pattern of molecules by EUV irradiation
  - Fragmentation of molecules after collisions with emitted electrons
  - Effect of thermalized electrons on resist molecules
  - Condensed resist material using nanoparticles

EUV Litho, Inc.

Workshop Summary: June 16 2016

- **2:30 PM Session 9: Resist -1**
- **<u>Mechanisms of Exposure of Resists to EUV Light: Photons, Electrons and Holes (P76)</u> (Invited)**
- Robert Brainard, *SUNY Polytechnic Institute, Albany*
- *Fundamental reactions between electron, photons and matter*
- ***Internal excitation of PAG by passing electrons***
  - *One electron can "photolyze" several PAG without being consumed*
  - *Can we detect this mechanism via fluorescent dye?* ***Cross section for excitation is low and key discoveries are needed before we can use this***
- ***Experiment / modeling of electron Blur***
  - *Thickness loss of resists – open source*
  - *Experiment vs modeling (code: LESiS)*
  - ***When reactivity of very low energy electrons (~ 3eV) is included – this can improve sensitivity a trade-off to electron blurr***

Workshop Summary: June 16 2016

- **2:30 PM Session 9: Resist -1**
- **<u>Fundamentals of X-Ray Excitation and Relaxation in EUV Resists (P78)</u> (Invited)** D. Frank Ogletree, *LBL*
- **Molecular Relaxation, Auger Emission and Fragmentation are intrinsic to EUVL**
- One EUV photon generates multiple secondary electrons in the PRIMARY event
- Our theoretical and experimental tools can be applied to more realistic resist component molecules
- *Process: Emission of photo electrons, Augur or fragmentation*
- **68 to 70 eV of residual energy in Xe+ after 4d photoemission**
- **Xe++ 2ed ionization, 21 eV energy**
- **Upto 48 eV available for Augur emission**

Workshop Summary: June 16 2016

- **Session 10: Resist -2**
- **<u>Fundamental Aspect of Photosensitized Chemically Amplified Resist: How to overcome RLS trade-off (P73)</u> (Invited)** Seiichi Tagawa, *Osaka University*
- ***New process – PSCAR (photosensitized CAR)***
- ***Early proof of principal results. Enhancement of sensitivity by 2x while LER and EL remain the same***
  - *Some fluctuations in sensitivity enhancement between various sites*
  - *Pattern degradation at low 2^{nd} flood exposure dose*
- *Only PS have absorption at the second flood exposure – no absorption by resist by the second exposure at 365 nm*
- *Consideration of new process*
  - *Reconsideration of acid generation process*
  - *Consideration of radiation and photo chemistry*

EUV Litho, Inc.

Workshop Summary: June 16 2016

- **Session 10: Resist -2**
- **<u>Molecular Resist Materials for Extreme Ultraviolet Lithography (P74)</u> (Invited)** Hiroki Yamamoto, *Osaka University*
- **We developed positive-tone chemically amplified molecular resist materials based on cyclic oligomers**
- The hole size of molecular structure is more important factor for sensitivity in EUV and EB resists
- The etching rate of noria derivatives is similar to that of conventional resist materials such as PHS, ZEP520A and UVIII

Workshop Summary: June 16 2016

- **Session 10: Resist -2**
- **Metal Oxide EUV Photoresist for N7 Relevant Patterns (P79) (Invited)** Stephen T. Meyers, *Inpria*
- Variation in effective does due to statistical distribution of absorbed photons and EL must accommodate this variation
- 18 nm contact, 2036 PAGs, 407 quenchers
- **High absorbance and small photoactive building blocks lower initial stochastic variability**
- **Improved dose vs LWR: < 20 mJ/cm^2 at N7 pitches**
- **Patterning: 13 nm L/S @ 26 mJ, 4.6 nm LWR**

EUV Litho, Inc.

Workshop Summary: June 16 2016

- **Novel EUV resist development for 13nm half pitch (P91) (Invited)** Yoshi Hishiro, *JSR*
- ***Material development for CAR performance improvement***
  - ***Acid diffusion control by high Tg resin & short acid diffusion PAG***
- ***Current status of JSR CAR@NXE3300***
  - ***LS***
    - ***13nmhp line resolution***
    - ***DtS: 25.2mJ/cm2, LWR 5.3nm@15nmhp***
  - ***CH***
    - ***18nmhp hole resolution***
    - ***Dts: 23.6mJ/cm2, CDU 3.23nm@22nmhp***

Want to know the latest on EUVL- Attend Our Upcoming Workshops!
Info at www.euvlitho.com

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

Thank you!

- I will like to thank following for making 2016 EUVL Workshop a very productive workshop!
  - Workshop Sponsors – Financial support
  - EUVL Workshop Steering Committee - Guidance
  - Session Chairs and Presenters _ Organization
  - Patrick Naulleau, Eureka and CXRO for hosting the workshop!
  - Juanita Spencer for the great organization!

- **Please complete and return the EUVL Workshop Survey!**