2017 EUVL Workshop

Workshop Summary

June 14-15, 2017

CXRO, LBL, Berkeley, CA

Workshop Summary: Wednesday, June 14, 2017

- **8:10 AM.....Welcome to LBL (P0)**

  Glen Kubiak, LBL

- Historical perspective on EUVL. Great photograph from first US-Japan on EUVL, October 1993!
- Showed slide from April 1996,with patterning results, that ended up saving the program.

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- **8:40 AM .....Session 1: Keynote - I**
- **EUVL: Current Status & Remaining Challenges** (P1) *(Keynote Presentation)*
  Obert R Wood II, *GLOBALFOUNDRIES*
- Source/scanner availability is not yet at the level needed for SE EUV CoO comparable to triple patterning 193i CoO at the 7 nm node.
- Resist resolution, LER, and sensitivity are adequate for 7-nm, but better LCDU will be required for future nodes.
- Mask blank defectivity and yield are continuously being improved:
  - Actinic tool will be needed for blank inspection, pattern mask inspection and defect repair verification at HVM.
- Three remaining topics that still need additional work are:
  - Mitigating stochastic effects:
    - with higher EUV doses to reduce photon shot noise (less desirable option)
    - developing new EUV resist materials with smaller reactive volume, more uniform distribution of components, fewer components & higher dissolution contrast
  - Compensating for EUV mask 3D effects.
  - Imaging with higher NA projection optics.

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- **EUV Lithography for HVM** (P3)

  (Keynote Presentation) Britt Turkot, *Intel Corporation*

- Exposure source → Significant progress: improvements in availability & power need to translate to field systems
- Pellicle → Needed to ensure EOL yield; pellicle program continues to make significant progress
- HVM requires predictability
  - Many factors affecting predictability for HVM
    - System availability
    - Pellicle transmission and power resiliency
    - Collector lifetime
  - OpEx (mostly source consumables) – DG lifetime improvement demonstrated in field; Collector lifetime improvements encouraging – need to translate to field systems
- Materials
  - Materials performance – Won't gate introduction of EUV, but need to emphasize stochastics: need to understand the interaction of EUV radiation with resist and design resist materials for stochastics

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10:20 AM…Session 2: EUV Masks and Mask Metrology

EUV Mask Economics: Impact of Mask Costs on Patterning Strategy (P33)
(Invited Paper) Bryan S. Kasprowicz, *Photronics, Inc.*

Masks are key to the success of EUV - Significant improvements made

- Mask manufacturing is maturing, approaching HVM readiness, BEOL focus
- Blank defect reduction is required to help improve mitigation process
- Infrastructure showing progress – ABI is good benchmark for success, AIMS in early stages in the field, APMI needed but lacks owner

EUV can be cost competitive to ArF with modest scanner throughput

- Cost model validates cost parity between one EUV mask and three high-end ArFi masks
- Reverses scaling trends, improves chip density; should allow for more chips/field and reduce cost

Modest EUV volumes are required to manage EUV Mask cost

- Earlier adoption will help drive crossover from ArF multi-patterning
- **Blank cost** is largest driver for HVM

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- **Reduction of Large Killer Defects in EUV Mask Blanks** (P39) (Invited Paper) Sandeep Kohli, *Veeco Instruments Inc.*
  - Overspray reduction >100X

    -larger target + improved ion optics with elliptical grid pattern
  - New ion optics qualified for process
    - Correlated with first 0-defect masks in quantity, as well as first 0-defect masks @ 54 nm (improved optics only)
  - Extended target + new ion optics proposed for larger overspray reduction
    - Would also enable lower gas pressure (for reduced gas scattering) with >100X overspray reduction
    - Target is fully functionally tested, not yet LDD qualified but low risk (relatively minor change)
  - Components are commercially available

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- **10:20 AM…….Session 2: EUV Masks and Mask Metrology**
- **NewSUBARU EUVL R&D Activities and EUV Mask Defect Inspection** (P34)
  (Invited Paper) Takeo Watanabe, *University of Hyogo*

- Fundamental research of EUV is processing at NewSUBARU, and resist, mask inspection, and collector mirror evaluation tool are developed.
- We have developed CSM systems for EUV phase and intensity imaging. **EUV PHASE IMAGING** is important to evaluate "mask 3D effect" and "phase defect".
- Standalone CSM system demonstrated pattern observation of cross pattern, absorber defect and L/S pattern.
- Micro-CSM system demonstrated actual defect characterization of phase defect and amplitude defect. (30 nm size)
- For factory use, EUV source and CMOS camera are key components. (under development)

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- **Anamorphic Imaging: Emulating Future Nodes of EUV Lithography on the SHARP Microscope** (P38)
  Markus Benk, CXRO
- SHARP High-NA Actinic Reticle Review Project
  - Emulation of imaging in EUV scanner
  - Emulation of anamorphic imaging
  - Uniform imaging performance and transfer of roughness in anamorphic imaging mode

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- **Characterization of SiN-based Membrane for EUV Pellicle Application** (P60) Jinho Ahn, *Hanyang University*

- SiNx platoform for pellicles – manufacturing options, thermal load simulation, optical characterization
  - 40 nm thickness, 80% transmission, 110 x 148 mm2 pellicle size
- If pellicle is not available , then proposed Shielded Reticle Mini Environment (SRME)

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- **RESCAN - A Standalone Tool for EUV Mask Defect Inspection** (P32) Patrick Helfenstein, *PSI*

- 10 nm CD error in 100 nm hp grating can be detected
- location accuracy defined by spot size and scan step width
- subsequently, fine inspection would be done using SCDI
- Developed fast detectors – hybrid CMOS detectors
  - 2 kHz acquisition rate
  - 10^6 photons/pixel dynamic range
  - 60% quantum efficiency
  - 75 µm pixel size
  - 50 e^- rms noise
- Development of a Compact source for actinic mask inspection

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- **Rigorous 3D Electromagnetic Simulation of Ultrahigh Efficiency EUV Contact-hole Printing with Chromeless Phase-shift Mask** (P37) Stuart Sherwin, CXRO

- Phase is **much** more efficient than amplitude
- Etched multilayer EUV mask works in theory and experiment
- Alternating phase-shift masks can only print certain patterns
- Need rigorous simulation to accurately design mask
    - Optimal design varies with pitch, pattern, and orientation

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- **kW-class Picosecond Thin-disk Pre-pulse Laser PERLA for Efficient EUV Generation** (P11) (Invited Paper) Akira Endo, *HiLASE*

- *Prepulse technology ready for >kW LPP and FEL*
- Technology platform of kW class picosecond thin disc laser established
- Extendibility to DUV and mid-IR for 100W class average power

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- **1:40 PM ..... Session 3: EUV Sources - I**
- **Scalability of CO_2 Amplifiers to Generate Stable > 500 W Extreme Ultraviolet (EUV) Beams** (P12) (Invited Paper)
  Koji Yasui, *Mitsubishi Electric Corporation*
- Scalability of CO_2 amplifiers to generate > 500W EUV beams that are

  required in the near future for high-volume-manufacturing of IoT/AI

  devices are discussed.
- We consider that with the emerging application fields related to IoT/AI

  technology, EUV lithography has become essential technology.
- We have shown that CO_2 amplifiers with transverse-gas-flow

  configuration could solve technological bottlenecks to enhance the EUV

  powers more than 500W.

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- **Simulating EUV Production – an Overview of the Underpinnings** (P13) (Invited Paper) Howard Scott, *LLNL*
- Simulation capabilities are improving
  - Macroscopic models based on higher fidelity microscopic models
  - Multiple physical processes with better coupling algorithms
  - Capability to test approximations with more fundamental methods
  - Larger, faster computers allow better models and/or higher resolution
- Confidence requires comparisons to multiple experiments
- Producing a predictive capability will take a dedicated effort

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- **Short-pulsed Nd:YAG Laser Interaction with Tin Micro-droplets** (P14) (Invited Paper) Oscar O. Versolato, ARCNL

- Study of ns ligamentation and hole formation in mm size water droplets
- Study of ns and ps pulse driven droplet propulsion

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- **3:30 PM……Session 4: EUV Sources - II**
- **Next Generation Source Power Requirements: What will we need at the 3 nm node and beyond?** (P15) (Invited Paper)

  Erik R. Hosler, *GLOBALFOUNDRIES*
- Source power must scale beyond 250W
  - Pellicles must follow w.r.t. survivability
- Potential for continued LPP scaling
- Disruptive sources still possible to intercept next major architecture change

- What should be the target source power (w/pellicle) for each progressive technology?
  - 7 nm → 250 W
  - 5 nm → 350 W
  - 3 nm → 500 W
  - '2 nm' → 1 kW
- ***Beyond?***

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- **A Compact LINAC-Driven EUV Light Source utilizing a Short-Period Microwave-Driven Undulator** (P16) Filippos Toufexis, *Stanford University*
- Short Period RF-Driven Undulator
  - **1.75 mm Period**
  - **4.9 mm / 2.4 mm In/Out Apertures**
  - Fed through the beam pipe
  - **1.4 MW for K = 0.1**
- Presented Technology Demo EUV Source Design
  - Thermionic RF Injector with RF Bunch Compression
  - Energy Recovery Structure feeds the Microwave-Driven Undulator
- **Potential for >100 W/mm^2/sr/0.1%BW**
  - Further R&D Required

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- **Concept for 1 kW EUV Source for Lithography Based on FEL Emission in Compact Storage Ring** (P17) (Invited Paper) Michael Feser, *Lyncean Technologies Inc.*
  - Design elements and conceptual feasibility of a 1kW coherent EUV source based on a small electron storage ring established
  - Next step is optimization of design with integrated simulation components
  - Followed by conceptual design study in preparation for engineering design
  - Components are using standard, practical and established technology
  - Extensible to higher power and shorter wavelengths (e.g. 6.x nm for future needs)

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- **Challenges to Realize the EUV-FEL High Power Light Source - Present Status on the EUV-FEL R&D Activities** (P18) (Invited Paper) Hiroshi Kawata, KEK
- Update of the EUV-FEL accelerator design is progressing from view points of end user demands.
- We organized EUV-FEL Workshop at last year and the R&D directions for accelerator technologies has been clarified; availability, size reduction, low operation cost, and so on.
- Staging procedure to the EUV-FEL light source for Lithography has been discussed with AIST, KEK, UTokyo, and EIDEC

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- **8:10 AM .....Session 6: Keynote –II**
- **Tabletop Coherent EUV Sources and Applications: Full Field Sub-Wavelength Imaging at 13.5nm and Materials Metrology** (P4) *(Keynote Presentation)*Margaret Murnane, JILA
- High harmonic sources are a unique quantum technology allowing exquisite
- control over EUV and soft X-ray light on a tabletop
- HHG technology is already a useful tool for materials/chemical/nano
- 1st 13.5 nm sub-wavelength EUV imaging
- Inspection, dopant profiles, sub-surface imaging, contamination detection
- Photoelectron & Photovoltage spectroscopies, In-situ materials growth monitor
- Thin film metrology
- Bright future – everything scales with the wavelength
- The limits of HHG technology are not yet known: 10keV, 50keV?

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- **High Power HVM LPP-EUV Source with Long Collector Mirror Lifetime** (P2) *(Keynote Presentation)* Hakaru Mizoguchi, *Gigaphoton*
- Pilot#1 is up running and its demonstrates HVM capability;
  - High conversion efficiency (5% level) is realized with several key engineering efforts.
  - EUV power recorded at113W average (85W in burst stabilized, 75% duty) with 5% conversion efficiency for 143hours operation in May 2017.
  - Pilot#1 system recorded Availability was 64% and idle time was 25%. Availability is potentially achievable at 89% (2weeks average).
- Long-life Collector Mirror mitigation test is in progress;
  - Superior magnetic mitigation (= 0.5%/Gp) has been demonstrated above 100W level operation with dummy mirror test.
  - Full scale C1 mirror life test is on going. Next target is >100W average power with high duty cycle operation with C1 full-scale mirror lifetime demonstration (Expectation from simulation: < 0.2%/Gp) .
- Further scalability scenario toward 300/500W EUV source power is under investigation

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- **EUV Lithography: Progress in LPP Source Power Scaling and Availability** (P5) *(Keynote Presentation)* Igor Fomenkov, *ASML*

- 14 NXE:33X0B systems operational at customers
- Significant progress in EUV power scaling for HVM
- Dose-controlled power of 250W
- EUV CE of 5.7%
- CO_2 development supports EUV power scaling
- Clean (spatial and temporal) amplification of short CO_2 laser pulse
- High power seed system enables CO_2 laser power scaling
- Droplet Generator with improved lifetime and reliability
- >700 hour average runtime in the field
- >3X reduction of maintenance time
- Path towards 400W EUV demonstrated in research
- CE is up to 6 %
- In-burst EUV power is up to 375W

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- **10:30 AM…..Session 7: Optics and Contamination**

- **EUV Optics Life-time Research: Past, Present and Future** (P21) *(Invited Review paper) (30 Minutes)* Norbert Koster, *TNO*
- We are moving into HVM, with associated problems:
  - Reliability
  - Increasing EUV powers
- Contamination control went from simple carbon contamination to complex photon/material interaction
  - New cap layers needed?
  - Material research
- We are almost at the end of the tunnel and the light is getting brighter

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- **10:30 AM…..Session 7: Optics and Contamination**
- **The Future of EUV Lithography: Enabling Moore's Law in the Next Decade** (P22) (Invited Paper) Jan van Schoot, *ASML*

- **High-NA extends Moore's Law into the next decade**

- Larger contrast of High-NA helps mitigating LCDU
- New anamorphic concept enables good imaging with existing mask infrastructure resulting in a Half Field image
- New stages technologies and high transmission enable throughput ~185WpH
- We are closing the feasibility, optics in design phase, first HW in place

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- **Latest Developments in EUV Optics** (P23) (Invited Paper)
  Jack Liddle, *Carl Zeiss*
- **Starlith 3400**

- Better POB
- Flexibility in illuminator
- Improved imaging
- Ready for 7nm and 5nm nodes

- **High-NA Anamorphic**

- Novel design concept
- Anamorphic design. Limits incident angles on mask, enables high contrast
- Obscuration. Limits incident angles on mirrors, enables higher tranmission.
- Infrastructure currently under construction

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- **EUV/SXR Optics and Metrology Development at RITE** (P24) (Invited Paper) Ladislav Pina, *RITE*
- *Review of GI collector optics*

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- **1:00 PM……Session 8: Resist and Patterning -I**

- **EUVL Developments at Imec** (P47) (Invited Paper) Greg McIntyre, *IMEC*
- Review of fundamental work at IMEC
- CNT pellicles, alternate mask absorbers, and study of high NA 3D mask effects

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- **1:00 PM……Session 8: Resist and Patterning -I**

- **Reactivity of Metal Oxalate EUV Resists as a Function of the Central Metal** (P41) (Invited Paper) Greg Denbeaux, *SUNU Polytechnic Institute*
- Between the three photoresists, a small change in EUV absorption does not account for the large change in E_{size}.
- Based upon our understanding of the photo-mechanism increased CO_2 outgassing should improve sensitivity.
- The rate of CO_2 outgassing seems to be correlated to the reducibility of the central metal.

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- **1:00 PM……Session 8: Resist and Patterning -I**

- **Novel EUV resist development for sub-7 nm node** (P43)
  (Invited Paper) Yoshi Hishiro, *JSR Micro Inc.*
- *Material development for breakthrough CAR performance*
  - *Acid diffusion control by high Tg resin & short acid diffusion PAG*
  - *CH : Well balanced sensitivity, LCDU and resolution. Ready for HVM.*
  - *LS : Promising resolution with wide process window and etch transfer.*
- *New metal resist development*
  - *16nmhp resolution was achieved by new Metal NP system.*
- *Sensitizer UL*
  - *The possibility of 16nmLS@under 10mJ was observed.*

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- **Metal Oxide Photoresists: Breaking Paradigms in EUV Lithography** (P50) (Invited Paper)Jason Stowers, *Inpria*

- MOx resists provide substantial opportunity for LWR improvement through etch
  - Truly evaluating RLS requires looking after etch

- Full potential of MOx resists extends beyond RLS
  - Unique etch properties: high selectivity, and separate etch "color"
  - Powerful integration schemes enabled

- Overall: MOx resists provide significant opportunities for additional gain by co-designing litho & etch processes

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- **Fundamental Aspect of Photosensitized Chemically Amplified Resist: How to overcome RLS trade-off** (P46) *(Tentative Title)* (Invited Paper) Seiichi Tagawa, *Osaka University*
- PSCAR is good solution for breakthrough of both RLS trade-off and photon shot noise problems.
- 125 keV EB exposure experiments at Osaka University showed very good results for PSCAR.
- Now collaboration partner companies have been examined PSCAR performance with the different types of PSCAR materials by simulation and EUV exposure experiments. Further optimization of PSCAR material formulation is needed but the initial results by preliminary off-line flood exposure experiments on ASML NXE:3300 at imec with TEL's standalone pre-alpha flood exposure tool are promising to understand the possibility of PSCARs.
- Improvement of optimization of processes, materials, and systems for PSCAR is always important, but improvement of PSCAR proceeds steadily and much faster than CAR. EUV CARs have been improved now very slowly but steadily by worldwide efforts based on the resist pattern formation model of EUV CARs including radiation chemistry even after 35 years since the birth of CAR in IBM.

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- **3:00 PM Session 9: Resist and Patterning -II**

- **Towards Real-Time Analysis of Morphologies using Scattering** (P42) (Invited Paper) Guillaume Freychet, LBL
- Study of line roughness - CD-SAXS on periodic roughness
- Combination of CD-SAXS/GISAXS for LER/LWR roughness

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- **3:00 PM Session 9: Resist and Patterning -II**
- **Extreme ultraviolet Induced Chemical Reactions in Photoresists and Model Systems** (P44) (Invited Paper) S. Castellanos, ARCNL
- EUV **absorptivity** of molecular hybrid photoresists **can be tuned** through their chemical structure.
- **Higher absorptivity** of Sn-based material compared to Zr-based materials **does not lead to higher contrast**.
- Tin oxocages undergo **cleavage of Sn-C bonds** upon low energy and high energy light irradiation.
- **Intermediate photoproducts** of Sn-based compounds are further reactive upon heating.
- Solubility switch of Zr- and Hf- based oxoclusters might occur through partial **decarboxylation** and ligand loss. The mechanism is under study.

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- **3:00 PM Session 9: Resist and Patterning -II**
- **Fundamentals of X-Ray Excitation and Relaxation in EUV Resists** *(Tentative Title) (P45)* (Invited Paper) D. Frank Ogletree, LBL
- Electron yield per molecule can be significantly ***increased*** by incorporating high cross-section atoms
  - Iodo-methyl Phenol ~ 10x
  - Fluro-methyl Phenol ~ 1.5 x
- Photoemission can create ***more than 2 electrons*** per molecule through Auger relaxation
  - Energy distribution is changed, can be two ~ 35 eV electrons instead of one ~ 80 eV electron
- Is this better or worse for pattern transfer ??
  - Better photon statistics
  - Can lower energy SEs reduce electron blur ?
  - Can multiple electrons drive "multi spur" chemistry ??
  - Can resist chemistries be tailored to exploit EUV photoemission?

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- **Fundamental Aspects of Low Energy Electron Driven Chemistry** (P48) (Invited Paper)Dan Slaughter, LBL
- Investigations of transient anion dynamics in other small polyatomic systems will provide a more detailed understanding of fundamental non-adiabatic processes.
- With deeper understanding of these fundamental processes, we can control chemistry of EUV photoresist materials at the level of individual electron-molecule interaction.