2009 EUVL Workshop Summary

(Notes taken during the meeting. Please report any inaccuracy to author.)

2009 International Workshop on EUV Lithography

July 13-17, 2009, Sheraton Waikiki, Hawaii

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EUV LITHO, INC.

Wednesday, July 15, 2009
Keynote Presentations

- R&D Status and Key Technical and Implementation Challenges for HVM Application of EUVL (KEY-1) *-Sam Sivakumar, Intel Corporation*
  - Moore's Law at Intel – selection of Lithography technology is key
  - **EUV being considered for 15 nm node 26-30 nm HP (2013) and 11 nm (18-20 nm HP) – need tools at least one year in advance**
  - **For EUV implementation need stable hardware, photoresist that meet requirements and Reticles**
  - **26 nm HP, 7.5 nm LWP for 17.8 mJ resist (Nikon EUV1 static data)**
  - **Sn LPP source from Cymer with 15-20 W capability has been shipped**
  - **Gaps**:
    - Resists typically about 2X from goal for sensitivity/ 5x for LWR
    - Source power about 10X from goal
    - Overall tool run rate requires ~ 20X improvement to 100 WPH goal
    - Reticle defectivity is a major concern. Gap to pilot 25 x to HVM 100 x.
    - Need actinic mask defect inspection tools and funding to support this development
    - Throughput is going to depend on Cost of Ownership
  - EUV has moved from research to implementation mode

Wednesday, July 15, 2009
Keynote Presentations

- Readiness and Challenges in EUV Mask Technology for 32nm-HP Node and Beyond (KEY-2) *Han-Ku Cho and Seong-Sue Kim, Samsung Electronics Co., LTD.*
  - **Mask Infrastructure has following key challenges**
    - Absorber stack optimization
    - Non-flatness correction
    - Blank defect and its mitigation
      - Pit smoothing via ML deposition
      - Pattern Placement Defect Mitigation
      - Need inspection tools
      - All real defects captured by wafer printing method are repairable
      - Coherent Scattering Microscopy – can measure defects on patterned area
      - Mask cleaning
      - E-Beam repair of defects
    - **100 x improvement in defects needed**
    - **5 x improvement in defect inspection tool throughput needed with 10 nm stage accuracy**

Wednesday, July 15, 2009
Award Ceremony

- “Lifetime Achievement Award” presented to Prof. Hiroo Kinoshita of Hyogo University for his contributions to the development of EUVL

- “Excellent Contribution Award” presented to Energetiq Technology, Inc. for the excellent performance of their EUV source

Wednesday, July 15, 2009
Session 2: EUV Source Technology

- High Brightness Next Generation EUV Lithography Light Source (SOURCE-1, Invited) *Sergey Zakharov, Nano UV and EPPRA*
  - Discussed limits of high power DPP and LPP sources and optimum source characteristics for maximum emitted power
  - Higher ionization stages of Xe are used to achieve higher conversion efficiency in the source
  - **Very Small etendue of < 10E-4 mm2.sr of individual source with multiplexd source etendue of 10E-2**
  - **Now twelve multiplexed sources are operational**
- Angular Distribution of the Ion Emission from a Tin-based Laser Produced Plasma Extreme Ultraviolet Source (SOURCE-2) Padraig Dunne University College Dublin
  - 4E11 W/cm2 power density (Nd:YAG)
  - **In-band energy represent 6 % of total energy between 10-18 nm range**
  - **Developed liquid mirror patented for LPP application**

Wednesday, July 15, 2009
Session 2: EUV Source Technology

- Molecular Dynamics Investigation on Tin (SOURCE-7)Majid Masnavi, Tokyo Institute of Technology
  - Physics of phase transition in the process of heating of Sn droplet that has been heated by a pre-pulse
  - Only a thin Sn layer below 40 nm gives efficient EUV emission
  - Target's time dependent development as a function of a laser power
  - **Physics of rapid heating (10E13 K/s) and cooling of Sn targets**
  - **Thermal history (pulse shaping is important) in determining the target performance**

Wednesday, July 15, 2009
Session 2: EUV Source Technology

- Fiber Lasers for EUV Lithography (SOURCE-6, Invited) Almantas Galvanauskas, University of Michigan
  - **Required laser power for LPP sources is 25 kW at 2% CE**
  - High wall plug to laser light conversion efficiency of 25-30% as compared to <10% for CO2 lasers, excellent COO as compared to YAG and Co2 lasers
  - 50 kW CW fiber lasers available today with M2=33, 2 % CE demonstrated for Sn droplet source
  - Per pulse energy limited to 4 mJ-10 mJ, although frequency can be increased
  - Power from single fiber cannot increase 1 kW with practical limit of 200-500 W
  - **Power achieved via multiplexing of 200-500 W (8-100 K Hz, 2-6 ns) modules**
  - **Multiplexing can be achieved via diffraction gratings , however issue of thermal load therefore sharp edge spectral filters are proposed – obtained M2=1.82, 52 W and 4 mJ pulse . System Can be ready in 4-5 years**

Wednesday, July 15, 2009
Session 2: EUV Source Technology

- LPP EUV Source Development at ETHZ (SOURCE-4) Ndaona Chokani, ETH Zurich
  - Focus of work on debris mitigation and thermal management of collector
  - Space resolved diagnostics of debris
  - Modeling of Time and space resolved distribution of radiation and debris (neutral and ions)
  - **Highly non-uniform distribution for Sn+3 and Sn+4 ionic debris**
  - **Debris KE goes up with ionization stage**
- EUV Source Technology Status (SOURCE-5) Vivek Bakshi, EUV Litho, Inc.
  - **Sn DPP – 10 W today (100% duty cycle) –fully integrated. Proof of principal for 50 W source**
  - **Sn LPP – 15-20 W system (x% duty cycle) shipped for integration. 75 W prototype (y % duty cycle) available in lab**

Wednesday, July 15, 2009
Session 3: EUV Optics

- Multilayer Optics for Next-generation EUVL Systems (OP-1, Invited) *Regina Soufli, Lawrence Livermore National Laboratory*
  - Review of latest deposition process technology
  - Optics Performance Review
  - **Detailed models of optics performance developed and validated**

- Use of Free Form Optical Surfaces for EUVL Projection (OP-2, Invited) *Russ Hudyma, Hyperion Development LLC*
  - **Goal is to achieve a "slot" or "rectangular field" geometry that can simplify the EUVL illuminator**
  - **Extend the "field curves" to "Field surfaces"**
  - Conceptual 0.53 NA 8-mirror system drives resolution
  - Obscuration enables wider node of zero aberration
  - **0.65 NA 8 mirror system proposed to turn ring field to a slot – using a "Zernike Surface"**
    - **Can be applied to obscured and unobscured systems**

Wednesday, July 15, 2009
Session 4: EUV Metrology

- High Accuracy EUV Reflectometry and Scattering at the ALS (MET-8, Invited) *Eric M. Gullikson, Lawrence Berkeley National Laboratory*
  - Need precise reflectometry for figure tolerance of 0.1 nm
  - To support Mask reflectometry, need wavelength Precision of 0.09 % and wavelength accuracy 0.09%, reflectance precision 0.36%
  - Scattering measurements of EUV Optics
  - **Reduced scattered light to improve reflectance accuracy**
  - **Web based data base**
  - **Measuring optical properties of photoresists**
- At-wavelength EUV Metrology at NIST (MET-4)*Charles Tarrio, NIST*
  - Absolute Cryogenic Radiometer (ACR) -based Diode Calibrations fbr high intenisties – better than 1%
  - Reflectivity uncertainty 0.35%, can handle 40 cm an 40 Kg samples
  - **Resist Sensitivity Measurements better that 15% accuracy**
  - **Attenuated EUV image plates**
  - **Scintillators for high resolution imaging**

Wednesday, July 15, 2009
Session 4: EUV Metrology

- EUV Reflectometry for Determining the Optical Properties of Photoresists and Underlayer Materials upon Irradiation at 13.5 nm (MET-7) *Fu-H. Kang, National University of Kaohsiung , Taiwan*
  - Empirical and simulation methods for estimation of reflectivity and absorbance
  - Measurement precision in a six month period +/- 9%
  - Stability of thin-film samples upon EUV radiation
  - **Measured EUV ablation rate for resists**
- ZnO Scintillator for Single-shot EUV Laser Focal Spot Imaging with sub-100 Picosecond Response Time (MET-1, Invited), *Nobuhiko Sarukura, Osaka University*
  - Hydrothermal method grown ZnO crystal
  - **High resolution imaging is under going**
  - **ZnO improved response time was demonstrated using XFEL**

Wednesday, July 15, 2009
Session 4: EUV Metrology

- Development of X-ray Tool for Critical-Dimension Metrology (MET-2) *Boris Yokhin, Jordan Valley Semiconductors Ltd.*
  - Small Angle X-ray Scattering (CD-SAXS)
  - **2 hours measurement time per wafer. XCD of 22. 6 cm – verified with SEM. Repeatability of 0.5%**
  - Measurement of trench height – measured 316 nm (verified by SEM 310 nm)
- Development of Ultra-fine Structure Metrology System using Coherent EUV Source (MET-5), *Hiroo Kinoshita, University of Hyogo*
  - **Target of actinic inspection is < 25 nm**
  - Actinic inspection using EUV microscope has been used
  - Coherent Scattering EUV Microscope (CSM) -uses HHG laser with resolution equivalent to the wavelength used
  - **Plan to produce 50 micro W using HHG**
  - **Have measured LS pattern of 100 nm HP**

Wednesday, July 15, 2009
Session 5: Contamination

- An Investigation of Debris Production by Various EUV Sources (CONT-1, Invited) *David Ruzic, University of Illinois at Urbana-Champaign*
  - Modified LADPP – optimizing source for debris mitigation study
  - **Measurement of debris at IF – energetic (100 eV) neutral atoms make to IF**

- Modification of Ru Surfaces during Simultaneous Irradiation of Thermalized and Energetic Sn Particles at Grazing Incidence (CONT-2, Invited) *Valentino Rigato, INFN Laboratori Nazionali di Legnaro, Italy*
  - **Mechanism of Ru sputtering and Sn Deposition (function of fluence and incidence angle)**
  - **Fluence in excess of 1E17 is needed at low energy for equilibirium steady state for Ru erosion**
  - Lower the grazing angle, the higher the deposition rate per unit done (lower lifetime)
  - Conversion of fast ions to thermalized particles in debris mitigation will reduce the erosion rate but will not in general enhance the collector performance

Wednesday, July 15, 2009
Session 5: Contamination

- Predicting Optics Damage Potential from Resist Outgassing Components (CONT-3) *Charles Tarrio, NIST*
  - Ranking of contamination potential of resists
  - Combine out gassing testing with lifetime testing
  - **Fundamental Study of mechanism of surface coverage by HC in presence of EUV photons**
  - **Need to know contamination rates below 10e-10 Torr and establish scaling laws for intensity**

- Absolute Total Ion Yield and the Relative Extent of Ionic Outgassing of Photoresists and Underlayer Materials upon Irradiation at 13.5 nm (CONT-4) *Yu-H. Shih National University of Kaohsiung, Taiwan*
  - NOVOLAC resist is stable upon radiation by 13. 5 nm
  - **Absolute total ion yield is dependant on the absorbance value and is in the order of 10e-3 and additional results**
  - **F+ outgassing is important for F+-containing compounds, in addition to hydrocarbons ions from resist and underlayer materials**

Wednesday, July 15, 2009
Session 5: Contamination

- Mask and Optics Contamination from outgassing, in-band, and out-of band exposures (CONT-5) *Gregory Denbeaux, University at Albany*
  - **Removing the SPF filter caused rapid contamination of mask (Carbon deposition)**
  - **Larger dose increase due to contamination that would be predicted by simple carbon absorption**
  - **Contamination topography affects required dose**

Thursday, July 16, 2009

- **8:00 AM Introduction / Announcements (Intro-2)**
  - Vivek Bakshi, EUV Litho, Inc.

- **8:05 AM Poster Session Awards (Presented by Session Chair for Poster Session: Ken Goldberg, LBNL)**

  - **First Place was a tie! Award given to two groups and accepted by following on the behalf of their groups:**

    Dr. Grace Ho (NUK) for Poster titled "A compact and ultrahigh-vacuum reflectometer for EUV applications " (MET-6)

    and

    In Wook Cho (Hanyang University) for poster titled "Line width roughness investigation through resist molecular structure in extreme ultra-violet lithography" (Resist-3)

Thursday, July 16, 2009
Session 7: EUVL R&D Status

- *Moderator: David Attwood (LBNL)*
- Panelists:
  - Greg Denbeaux – USA (U Albany) (R&D -1)
    - Overview of Current Research Activity at: Intel, U Albany, SEMATECH, LBNL, College of Nano scale Science and Engineering, AMD
  - Hiroo Kinoshita –Japan (University of Hyogo) (R&D -2)
    - Programs Since 1999 and presented plans until 2010
    - EUV Resist Programs at University of Hyogo, Selete, Osaka University
    - Mask Programs at Selete, University of Hyogo with collaboration with Samsung
  - Padraig Dunne – Europe (University College, Dublin) (R&D -3)
    - University programs: Ireland, Switzerland, Italy, France, Germany, The Netherlands, Belgium, Russia, Sweden, Poland, Czech Rep, UK
    - Suppliers: ASML, Philips Extreme, Media Lario, Xtreme
    - Many Government supported programs

Thursday, July 16, 2009
Session 7: EUVL R&D Status

- Grace Ho – Taiwan (National University of Kaohsiung) (R&D -4)
  - National Science Council (NSC) funds university research
  - ASML, TSMC and PSC are interested in this project and Nissan Chemical Industry Ltd. collaborates with the resist subproject
  - Addressing critical issues and benchmarking with others.
- Jinho Ahn – Korea (Hanyang University) (R&D -5)
  - National Center for Nanomaterials Technology
  - Programs in Mask Fabrication and cleaning, EUV resist and out-gassing, Infrastructure development
- **Feedback :**
- **Exchange of Students to promote interaction**
- **How to address LER – as that may be the limiter for optical lithography – need a special session on this topic**
- **Request to invite SRC to the workshop**

Thursday, July 16, 2009
Session 8: EUVL Mask

- Optimizing the Mask Structure for Extreme Ultraviolet Lithography (MASK-6, Invited), *Jinho Ahn, Hanyang University*
  - R&D focused on ML Interface Engineering, Adhesion Force Study, Cleaning Efficiency (LSC) and absorber stack
  - Effect of absorber thickness on mask shadowing
  - Phase shift masks for 0.32 NA system
  - **Comment: need to look at the diffracted pattern in order to optimize mask design**
- Wavelength-Specific Reflections: A Decade of EUV Mask Inspection Research (MASK-4, Invited) -*Kenneth A. Goldberg, LBNL*
  - **13.5 nm can penetrate all ML layers and look at phase defects at the substrate- something you cannot do at other wavelengths**
  - Recommend paper on MIRAI design by Tezuka, JJAP 45 (6B), 2006
  - Coherent EUV Scattering Microscope (CSM), PEEM Microscope and Zone plate microscope

Thursday, July 16, 2009
Session 8: EUVL Mask

- Study of Critical Dimensions of Printable Phase Defects Using an Extreme Ultraviolet microscope (MASK-3, Invited) *Hiroo Kinoshita, University of Hyogo*
  - **Resolution of pattern inspection of 55 nm and defect inspection of 50 nm width and 2 nm depth is achieved**
  - **Cooling of CCD improved resolution**
  - **Critical dimension of pit on glass is 2 nm in depth – defects need to be smaller in order not to get printed**

- Zoneplate lenses for EUV Microscopy (MASK-5) *Iacopo Mochi, LBNL*
  - AIT images : 65 nm limes (16.25 nm 4x) can go down to 60 nm

Thursday, July 16, 2009
Session 9: Panel Discussion : Actinic Defect Inspection Technology for EUVL Masks

- Moderator: *Vivek Bakshi (EUV Litho, Inc.) :*
  - Introduction of Panel Discussion Topic (Mask Panel -1)
- **Panelists:**
  - Mask Panel-2, *Takeo Watanabe (University of Hyogo)*
    - **To reach throughput of 3 Hrs per mask need >86.5 W (0.03 x 0.03 mm2 area) with etendue of 3.2 E-2 or brightness of ~3E3 W/mm2.sr. It may be difficult to achieve!**
      - With observation time of 0.4 ms. Less power for smaller throughput
    - For CMS – current source power ~1.2 pW need >0.7 nW
  - Mask Panel-3, *Debbie Gustafson (Energetiq)*
    - Large variation in metrology supplier requirements
    - Difficult for industry to meet brightness requirements for patterned mask inspection with LPP sources
    - **Current brightness 8 W/mm2sr with plans to scale up to 18 W/mm2sr (0.3mm FWHM) – will get reduced by 60% due to current debris mitigation**

Thursday, July 16, 2009
Session 9: Panel Discussion : Actinic Defect Inspection Technology for EUVL Masks

- Mask Panel-4, *Sergey Zakharov (Nano UV)*
  - Source as bright as Synchrotron Light sources or even brighter are needed today to achieve required performance
  - Etendue is much smaller for these sources 10-E2 to 10-E4 mm2.sr
  - 0.1 W/cm2 at 3.3 kHz
  - 0.32 degree emission angle (9E-5 sr) with etendue of 9.7E-5 mm2.sr
  - **Brightness of 50-60 W/mm2.sr with 200 W/mm2.sr demonstrated**
  - With plasma lens etendue can be reduced to <10-E4mm2.sr
  - For 12 multiplexed sources etendue of 10E-2 mm2.sr

- Mask Panel-5, *Eric Szarmes (University of Hawaii)*
  - Compact brightness source with CW S-band Superconducting LINAC and 10kW, 2.86 G Hz, Phase Locked CO2 laser
  - Half angle of 10 mrad
  - Brightness of 10kW /mm2.sr (Projected value)

Thursday, July 16, 2009
Session 9: Panel Discussion : Actinic Defect Inspection Technology for EUVL Masks

- Mask Panel-6, *Hironari Yamada (Ritsumeikan University)*
  - EUV produced by a small target (Cu wire target of 5.5 micron)
  - Source size 1 micron x 3 mm with 5 mrad spread
  - In 2% BW 0.283 mW, source area 3E-3 mm2
  - B=900 kW/mm2.sr
  - Can increase operation to 10kHz

- Mask Panel-7, *Vivek Bakshi (EUV Litho, Inc.)*
  - **Presented method for brightness calculations**
  - **Proposed specs for EUV Sources to support actinic inspection**

Thursday, July 16, 2009
Session 10: EUV Resist

- Development Status and Future Prospect of Extreme Ultraviolet Resists (RESIST-9, Invited) *Takahiro Kozawa, Osaka University*
  - How to increase resist absorption and quantum yield
  - LER is still away from target while sensitivity is getting close to requirements
  - **Increase of pattern formation efficiency is required to decrease LER without increasing exposure dose**
  - **Methods of enhancement of chemical gradient were proposed**

- Molecular Resist Materials for EUVL Lithography: What Might Be Possible and How Do We Get There? (RESIST-11, Invited) *Clifford L. Henderson, Georgia Tech*
  - Molecular resists– need single molecule resists that contain PAF functionality and acid labile protection function
  - Negative Tone MRs –outstanding results for LER, sensitivity and resolution

Thursday, July 16, 2009
Session 10: EUV Resist

- EUV Interference Lithography (RESIST-10, Invited) *Harun H. Solak, Paul Sherrer Institute*
  - Grating masks with 20-50 nm HP, 35 to 2000 nm pitches, 1 wafers/hour throughput, stable flux 10-50 mW/cm2
  - Resist Evaluation – dose for resist 30-40 mJ/cm2
    - Line/space patterns in PMMA 25 nm
    - Calixarene resist patterned with 12.5 nm resolution
    - **FOX12 –HSQ (Dow Corning) 11 nm**
    - EUV resists can be patterned up to 21 nm (Contact holes)
  - In the process of upgrade of beamline
- EUV Interference Lithography in New SUBARU (RESIST-6) *Takeo Watanabe, Hyogo University*
  - 11 m undulator
  - Coherence length of >1 mm
  - 25 nm HP demonstrated (using PSI grating)

Thursday, July 16, 2009
Session 10: EUV Resist

- Monte Carlo Simulation of Chemical Intermediates in CARs (RESIST-4) Akinori Saeki, Osaka University
  - Monte Carlo Simulation of LER
  - Min LER Decreases with Development time exposure dose and line width
  - **LER of 1.2 nm is achievable by fine tuning exposure dose, PEB time and process conditions. Need comparison with experiments**

Thursday, July 16, 2009
Session 11: LER

- Stochastic Approach to Modeling Line Edge Roughness in Photolithography (RESIST-8, Invited) Chris Mack, Lithoguru.com
  - With continuum approximation we cannot predict line edge roughness
  - Stochastic view of exposure reaction
  - **Some diffusion length value will optimize LER**
  - **Need to include base quencher and development rate uncertainty**

Thursday, July 16, 2009
Session 11: LER

- How Will Wafer Plane Line-edge Roughness Requirements Impact Mask Specifications? (RESIST-7, Invited) *Patrick P. Naulleau, LBNL*
  - Correlated LER= 3.4 nm= Full LER* Sqrt (correlation)
  - Current LER requirements indicate replicated roughness limits near 50 pm
  - **Proposed mask roughness specs -No specs in ITRS for mask roughness**
    - **22 nm HP- total LWR allowed 1.7 (8% of CD) nm- Mask can have only 10% impact on LER (mask can have LWR of 0.7 nm)**
    - **16 nm HP- total LWR allowed 1.3 nm (8% of CD), mask contribution 0.5 nm (10% impact)**

- Sub-22 nm Line and Space patterning using Resist Reflow Process for Extreme Ultra-Violet Lithography (RESIST-2) *In Wook Cho, Hanyang University*
  - Simulation results via Monte-Carlo and Resist Reflow Process

Thank you

- Thanks for making 2009 EUVL Workshop a success! Special thanks to
  - Steering Committee
  - Session Chairs
  - Presenters
  - Sheraton Waikiki Staff
  - Darlyne Harlan, Mat Harlan, Mario Gonzales, Nina Perales, Dan McGowan
- **See you again in June, 2010 in Maui, Hawaii!!**
  - **Tentative plans for the Week of June 20th**