2017 Source Workshop

Workshop Summary

Vivek Bakshi

EUV Litho, Inc.

Welcome to UCD by Prof. Feely

- New Science building is the largest single investment in science in Ireland
- Mentioned her background at UC Berkeley and her meeting with Gordon Moore
- Delighted to have meetings on campus that helps in continued extension of Moore’s law

Workshop Agenda: Tuesday, November 7, 2017

- **9:35 AM Session 1: Keynote-1**
- **EUV Source for High Volume Manufacturing: Performance at 250 W and Key Technologies for Power Scaling** (S1) (Keynote Presentation) Igor Fomenkov, *ASML*
- *Eight years to decide on Sn LPP as the technology for HVM*
- ***Resist sensitivity is a major driver for source requirements (5 mJ to 35 mJ)***
- *Currently 15 systems running in field, >1.4 Million wafers processed, devices next year*
- *Pellicles and DGL. DGL as OOB filter. Composition? Absorption?*
- ***Photograph of Sn LPP in hydrogen background***
- *3D modeling with asymmetric profile*
- *Dose overhead principal?*
- *Angular dependence of forces on the droplets. Droplets need to move fast with max space between droplets. 16 micron droplets with 1 micron space unstability. 1.5 mm separation at 80 K Hz*
- ***Source power 250 W, CE 6%, CO2 40 kW, 50 K Hz, 21.5 KW, 41% collector reflectivity, enhanced isolation technology, advanced target formation technology, dose control. Droplet generator lifetime of 4 month. Success with Hydrogen. Almost no microparticles.<0.4% loss over GP. 375 W in burst at 50 kHZ. 400 W on research platform. 8 years of engineering!***
- ***Non-uniform degradation of collectors – what are the issues with imaging. How we address this (question from audience)?***
- ***125 WPH with help via faster wafer swap,….***

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- **10:40 AM Session 2: Fundamental Data**
- **Tin Ion Spectroscopy on Plasma Sources of EUV Light** (S14) (Invited) Ronnie Hoekstra, *ARCNL, The Netherlands*
- *EBIT and LPP based study of Sn 7-15+, LPP spectroscopy of low charged Sn 3-5+*
- ***Line identifications and energy level** and population dynamics*
- *7-12 nm OOB from Sn 15+ to 8+, > 13.5 nm from 8+ to 14+*
- *After identification by O'Sullivan in 1994 – first stab and best for almost 25 years*
- *Optical spectra of low charge state tin, line intensity as a function of laser pulse energy*
- *Identification of lines from Sn I-V, **SIV 47 lines – not identified before, only 20 lines can be linked to known levels. 0.1% uncertainty corresponds to 5 nm shift***
- ***Database: ISAN EUV Spectroscopy 2006, NIST Moore 1958***
- ***New IP value for Sn , added 12 new terms, identified new levels, not included dynamics***

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- **Atomic Data of Low-charged Sn ions for Lithography Applications** (S11) (Invited) J. Colgan, *LANL, USA*
- No complete tables of Sn opacities
- Description of how the radiative properties change over plasma properties
- CI vs IC calculations example (CI more accurate)
- Ways to speed up calculations – 2-mode approach
- Very difficult undertaking to take atomic data and integrate it into modeling

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- **EUV Spectra of Highly Charged-ions Observed with a Compact Electron Beam Ion Trap** (S12) (Invited) Nobuyuki Nakamura, *UEC, Japan*
- *EBIT – narrow charge distribution, low Ne, dominated by transitions to the ground sate*
- *Charge state that should be assigned to each transition can be determined from electron energy*
- *6.x nm – comparison of experiment and theory for Gd to Hf*

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- **Fundamental Studies of Sn^{7+}-Sn^{14+} Ions with Applications for Laser - produced Plasma Sources** (S13) (Invited) H. Bekker, *Max-Planck-Institut, Germany*
- *260-770 nm spectrum from Sn*
- *Sn 13+ - only one transition*
- *Photoionization cross-section measurements*
- *Low-cost mini-EBIT*

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- **12:00 PM Session 3: Lasers**
- **High Average - power and High - energy Ultrafast Thin-Disk Amplifiers** (S31)
  Thomas Metzger, *TRUMPF*
- Overview of laser offerings
- *Trumicro 5000: 100 W ~ 1 ps, 300 K Hz, 36 pass cell design*
- *Multipass design for 1 kW*
- *3kW at 10 K Hz, 10 ns, M2 11*
- *XUV generation using Trumpf lasers – Examples See HHG and inverse Compton*
- ***1 kw, 1-200 mJ, M2 1.12 to 1.4, 0.7 to 1.5 ps***

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- **High-harmonic Generation for Metrology Applications** (S32) (Invited)
  Johannes Weitenberg, *Max-Planck Institute, Germany*
- HHG Applications Review
- Design for HHG at high rep rates > 10 MHz
- High power Yb:YAG – 400 W, M2<1.2, 1030 nm, 0.85 ps
- Nonlinear pulse compression to enable higher power XUV sources

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- **Development of kW-level Picosecond Thin-disk Pre-pulse Laser for High-power EUV Sources** (S33) J. Mužík, *HiLASE, Czech Republic*
- Requirements for pre-pulse lasers:10 mJ, 1-2 ps, 100 K Hz, ? W
- 450 W, 9 mJ pulse energy
- Fourth harmonics, 205 nm – potential for pre-pulse for EUV

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- **2:00 PM   Session 4: High Power LPP Sources**
- **High Power LPP EUV Source with Long Collector Mirror Lifetime for HVM** (S41) (Invited) Hakaru Mizoguchi, *Gigaphoton, Japan*
- 5.5% CE from 4.7% by optimizing pre-pulse
- Present system has potential for 320 W and capable of 500 W (via 40 kW lasers)
- Choice of cap layer material allows no damage to cap layer
- Pilot #1, 113 W 5%CE, 89% availability

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- **Two-dimensional Electron density and Temperature Profiles of EUV Light Sources with 4.0% CE** (S42) (Invited) Kentaro Tomita, *Kyushu University, Japan*
- Thompson Scattering system – 20 mm resolution to measure Ne and Te
- Can explain change in CE using 2D plasma parameters
- CE calculations by calorimeter and Thompson scattering
- Top-hat laser profile may help with CE

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- **Short-wavelength Out-of-band EUV emission from Sn Laser-produced Plasma** (S43) Francesco Torretti, *ARCNL, The Netherlands*

- Sn 9+--13 [Ref: arXiv 1709 02626 (2017)]

- **Correlate results in 1-10 nm with models**
- Measured the EUV spectrum from Sn droplets irradiated by high-energy 1064 nm laser pulse
- Using the flexible atomic code, we identified the line features in the 7-12 nm region
- Our calculation results excellently agree with the measurements
- The calculations can be used to identify the charge sate balance observed in the spectrum

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- **Vapor shielding of Tin Under Intense Plasma Bombardment** (S45) (Invited) T.W. Morgan, *DIFFER, The Netherlands*

- Liquid metals are immune to most issues from solids in fusion reactors
- Vapor shielding – additional loss channels for heat flux
- Shielding reduces temperature of surface of tin and is oscillatory in nature

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- **ARCNL Source Project Update** (S46) (Invited)
  Oscar Versolato, ARCNL, The Netherlands
- Facility and program overview
- ns pulse driven droplet propulsion and comparison with water droplets
- ps prepulse – different physics, spherical deformation at low energies and fragmentation at higher energies - capillary retraction of stretched spherical shell – depends on wave number
- New line identification
- Ion kinetic energy distribution

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- **4:00 PM Session 5: EUV Source Modeling**
- **Towards High-Fidelity Simulations of EUV Production from Laser-Produced Plasma** (S22) (Invited) Howard Scott, *LLNL*
- Predicting trends does not depend on details but correct assumptions
- Data must cover al charge states upto 28+
- Controlled approximations can allow high-fidelity simulations are available (how 147K can be reduced to 1K)

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- **4:00 PM Session 5: EUV Source Modeling**
- **Modeling of Particle Debris from the Target of Laser Produced Plasma EUV Sources** (S24) Akira Sasaki, NIQRST, *Japan*

- CO_2 laser is absorbed by particles generated during pre-pulse
- Bubble appear inside the liquid targets and then grows to breakup the droplet
- Below critical temperature, particles do not form

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- **Atomic and Radiative Processes in High-Z Plasmas and their Applications** (S21) Bowen Li, *Lanzhou University, China*

- Quasi-Moseley’s law if n=0 4d-4f is validated
- Enhancement of radiation via use of dual laser
- Soft X-ray (SXR) spectra from Hf and Ta LPPs were recorded in the 1-7 nm region, some prominent features in the spectra are identified.

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- **Soft X-ray Spectroscopy of Dy, Er and Tm Ions Excited in Laser-Produced Plasmas** (S23) John Sheil, *UCD, Ireland*

- Identified structure in the $\Delta n = 0$ arrays: Ag -, Pd - and Rh - like emission.
- Tentative identifications: Sr – like transitions $4d^2\ ^3F_2 - 4d4f\ ^3G_3$.
- Identified wavelength bands arising from 4f – 5g, 4d – 5p transitions and their corresponding 5s satellite arrays.

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- **9:20 AM Session 7: Keynote Session -2**
- **Imaging Biological Cells using Soft X-ray Tomography** (S2)*(Keynote Presentation)* Carolyn Larabell, *UCSF and LBL, USA*
- Noted progress in the development of sources
- 6 Hours at diamond, 10 mins from new setup from Hans Hertz – this is progress from Source community!
- Looking to inspire source developers as the applications are enormous for water window microscopy

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- **10:00 AM Session 8: Metrology Sources**

- **Plasma based XUV Sources for Metrology Applications** (S53) (Invited) Klaus Bergmann, Fraunhofer, Germany
- Comparison of 6.x nm emitters
- Proposed CuMgGd alloy with melting point <500 C – gives strong Mg line at 6.7 nm
- Long term behavior of conversion efficiency
- J. Phys. D Applied Physics 2017
- **Proposal for further optimization of CE based on more efficient use of discharge current**

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- **Characterization of Laser-assisted and Laser-driven EUV sources for Metrology Applications** (S51) (Invited) Yusuke Teramoto, *BLV Licht- und Vakuumtechnik GmbH, Germany*
- 200 x 400 micron size and brightness of 200 W/mm2/sr (145 area-averaged brightness)
- Brightness increased via operation frequency, laser time delay
- Position stability 6 micron
- Use two lasers with second laser being weak one with few mJ per pulse only – it is used to increase the electron temperature of initial plasma
- Compact EUV X-ray source (laser and Sn target): 15 kHz, 76 W/mm^2/sr, CE<1%,3-5% stability pulse to pulse. Position stability 2-5 micron pulse to pulse. May apply the same debris mitigation technique as in LDP.

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- **Session 8: Metrology Sources**
- **Actinic Light Source based on LPP for HVM Mask Inspection Applications** (S55) (Invited) Samir Ellwi, ISTEQ, The Netherlands
- Li source system layout
- 1kW drive laser for beta source, brightness of 1000+, design per specs of customer
- 2KHz
- CE 1.2%, shorter pulse reduces the debris

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- **Session 8: Metrology Sources**
- **Laser Induced Shockwave Droplet Breakup Dynamics** (S52) Duane Hudgins, ETHZ, Switzerland
- **Simulation of breakup dynamics, using fluid models**
- **Fragments spatial distribution depends on laser spot size**
- Fluent VOF CFD simulations of the droplet breakup were used to determine the fundamental mechanisms governing neutral cluster fragment size and spatial distribution
- Large velocity gradients induced in the droplet lead to a high stretch rate of the expanding droplet sheet
- As the sheet thins, capillary destabilization causes perforations to form in the sheet that grow to form ligaments that fragment into droplets
- The droplet fragments scale as $d_D \approx 1.21 \cdot D \cdot We_s^{-1/4}$
- The analytical models are tools to estimate how system parameter changes in droplet size, laser pulse energy, positional stability, etc will influence the splash flux to the ML collector
- This model can be used to help determine an optimal positional range of the ML collector mirror
- **Further work will focus on determining how the droplet shape irregularities and laser alignment influence the fragment sizes and debris spatial distribution**

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- **A High-brightness Accelerator-based EUV Source for EUV Actinic Mask Inspection** (S54) (Invited) Y. Ekinci, *Paul Scherrer Institute, Switzerland*
- APMI using CDI – requires much higher brightness than other methods
- *Previou ssources - Helios – Oxford instruments -10 W, Aurora – Japan – 10 W*
- *Requrirements – 7 hours, 0.1% stability, <5% schduled, <1% unschduled downtime*
- *COSAMI – 100 mW, 10E9 W/mm2.sr*
- *50 ps every 2 ns, footprint - (size of a laser)*
- *Photo-injector LINAC using UV lasers*
- *CDI method restrictions on dynamic range?*

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- **Compact X-ray Sources and Applications for Semiconductor Metrology** (S56) (Invited) R. Joseph Kline, *NIST, USA*
- X-ray metrology based solutions
- CD SAXS – need 10-100 x brighter sources
- Review of X-ray source technologies
- Brightness and stability of various sources reported in a separate publication
- X-rays have potential to solve critical metrology challenges to semiconductor industry
- New X-ray sources with much increased flux would enable a number of game changing new measurements
- A number of new source technologies are under development with potential to substantially enhance the current source capability

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- **12:15 PM   Session 9: Broad-band Sources**

- **Industry Requirements for Broad Band EUV Sources for Wafer Inspection Applications** (S61)
  Vivek Bakshi, *EUV Litho, Inc., USA*
- Presented reasons for needs for a broadband source and related pieces of puzzles and next steps for industry
- Presented Draft version of requirements for broad-band sources

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- **12:15 PM Session 9: Broad-band Sources**
- **High Power Laser-Sustained Plasma Light Sources for KLA-Tencor Broadband Wafer Inspection Tools** (S63) (Invited) I. Bezel, *KLA-Tencor Corp, USA*
- **Will like 120-250 nm, broad-band, ML optics**
- **120- 200 nm region suggested for broad-band sources but worth looking into 50 nm region**

- LSP plasmas are complicated. Optimal LSP operating conditions depend on the spectral region for collection, etendue requirements, and available pump power. Accurate modeling and understanding plasma behavior are required to succeed in building an optimal source.
- Plasma confinement is one of the most challenging problems for higher power operation. Fascinating physics is happening there!

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- **The Electrode-less Z-Pinch as a Metrology Source in the 40-50 nm range** (S62) (Invited) Stephen F. Horne, *Energetiq, USA*
- **20-50 nm – Neon Ne 3+ looks promising (Lots of praises for NIST database)**
- Theoretically, we should be able to produce significant power between 20 and 50 nm.
- In a very crude and un-optimized experiment, we estimate 19 W/2PI in this range, with 4 kW input power (could go to 7 kW)
- If we can increase pressure and avoid wasting energy on high charge states, 100 W should be possible.

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- **2:30 PM Session 10: Applications**
- **Soft X-ray Microscopes for Biology: The Source** (S71) (Invited) Gerry McDermott, *UCSF & LBL, USA*
- Growth of biological soft X-ray microscopy is limited by source availability!
- Exposure time of seconds is OK , ms is luxury
- **New sources just need to be ‘good enough’ and does not need to equal a synchrotron (100 ms at synchrotron and 10 s is OK)**
- **Source does not help if you do not have a microscope!**

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- **Chromatin Reorganization during Viral Infection** (S72)(Invited) Maija Vihinen-Ranta*, University of Jyvaskyla, Finland*
- Virus remains latent in neural cells
- Fascinating review of work conducted in the application of water window microscopy

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- **Exploring the Soft X-ray Radiance of Laser Plasmas** (S73) (Invited)
  Fergal O’Reilly, *UCD, Ireland*
- Exploring Radiance
- Plasma size experiments to image plasma <5 microns
- Demonstrated high CE from sub 10μm plasmas – smaller is not always better
- Much more space to optimise into

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- **Relativistic Plasma Control using Two-colour Fields** (S75) (Invited) Brendan Dromey, *Queen's University, UK*
- Surface high harmonic generation (SHHG) mechanisms (**brief overview**)
  - Coherent Wake Emission
  - Relativistically Oscillating Mirrors
- The role of plasma scale length and experimental control

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- **Spectroscopic EUV Reflectometry for Characterization of Thin-films Systems and Determination of Optical Constants** (S76) (Invited)
  Larissa Juschkin, *RWTH Aachen University, Germany*
  - EUV spectroscopic reflectometry is a powerful tool for analysis of thin films and film stacks with high surface/material sensitivity
    - **non-destructive analysis of ultra-thin films**
    - **strong element selectivity**
    - **determination of chemical bonds (NEXAFS)**
    - **surface sensitive technique (up to ~100 nm)**
    - **surface roughness determination**
    - **potential for sub-µm spatial resolution**
    - **simultaneous acquisition from one measurement**
  - Laboratory EUV light for future metrology tools with high spatial resolution and throughput capability
  - Pulse to pulse analysis allows to be independent on source fluctuations
  - Multi-angle measurements allow to increase precision and stability
    - **experimental determination of EUV optical constants**
    - **determination of layer density and stoichiometry**
  - Responsive quality control method due to high sensitivity to chemical composition and sample structure

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- **4:30 PM Session 11: Optics and Metrology**
- **EUVL Optics for Free Electron Laser Sources: Damage Threshold Studies and the Use of Adjusted Wavelengths** (S82) (Invited)

  Eric Louis, *University of Twente, The Netherlands*
- **Shift to 12.6 for FEL, 20-25% higher transmission in a scanner (for a narrow band so need to keep central wavelength under very tight control)**
- Investigation of ML damage (with Ru cap) for FEL. Power per pulse will be 10 x lower but there will be increase of 10E5 in terms of peak density.
- After 16 M shot some loss in reflectivity due to oxidation of top layer but no indication of in-depth multilayer damage.

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- **Novel Spectrometers for Broad-band Characterization of EUV-Emitting Plasmas** (S83) V V Medvedev, *RnD-ISAN, Russia*
  - Developed compact grazing-incidence spectrometer for broadband SXR-VUV spectral measurements
    - Spectral range 5-200 nm
    - Spectral resolution up to 50 in the range in 1st diffraction order
    - Spectral resolution up to 100 in the range in -1st diffraction order (but limited spectral range)
  - Developed grazing-incidence spectrometer for high resolution measurements in EUV range
    - Spectral range 10-40 nm
    - Spectral resolution up to 600

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- **Broadband Spectral Characterization of EUV light Sources with a Transmission Grating Spectrometer** (S85) Muharrem Bayraktar, *Univ. Twente, The Netherlands*
- 1st time spectroscopic measurement in a production EUV source
- Using a novel transmission grating spectrometer
- Spectra measured in EUV, DUV-NIR ranges from the same port
- Emission lines match with reported line positions
  - EUV UTA: Sn^{12+}-Sn^{17+}
  - EUV < 12 nm: Sn^{8+}-Sn^{15+}
  - DUV-NIR: Sn^{2+}-Sn^{3+} and H^{+}
- Absolute calibration of spectrometer in progress