2019 EUVL Workshop

Workshop Summary

June 12-13, 2019

THE CENTER FOR X-RAY OPTICS

EUV Litho, Inc.

Workshop Summary – June 12, 2019

- **Session 1: Keynote - I**

Canonical Phase Measurement in Quantum Mechanics (P1) (Keynote Presentation)

Irfan Siddiqi*, UC Berkeley and LBL*

- Overview of Quantum Computer revolution
- What makes an electrical circuit quantum?
- A qubit is just an non-linear oscillator
- Measuring Qbit states via microwave reflectivity
- 8 qubit chip uniformity requirements
- True measurement of phase
- Advanced quantum testbed.
- Key questions for next 5 - 10 years.
  - How do we stabilize quantum coherence in an open many-body quantum system? What does physics look like at the edge of the complexity frontier?

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- **EUV lithography Today and Extension for the Next Generation (P2) (Keynote Presentation)** Britt Turkot, *Intel Corporation*
- Scanner availability continues to improve with significant recent improvements, but this area remains in focus. It was noted that time to repair droplet generator was significantly reduced over last two years.
- Collector lifetime and source power has also significantly improved (only qualitative data was presented)
- Confirmed 250 W of power in field – a significant jump from 150 W
- Improvement in defect address to the mask during manufacturing and these adder events remain unpredictable
- Pellicles: > 83% transmission, reflectivity < 0.04%, transmission stability of 0.8% at 250 W for 600 wafer exposure
- Mask blank defect size is going down and improvement in its location accuracy from 3rd generation inspection (needs higher sensitivity blank inspection with better location accuracy)
- EUV AIMS meeting expectations and so is APMI tool for full mask inspection. Gave example of captured defects
- Area of focus for high NA are material and masks
- Metal cluster resists show better CDU than CAR. Chain scission resists show even better CDU but with a high dose. They also show impressive resolution (11 nm CH, 28 nm L/S)
- See next two slides for a detailed state of challenges and summary of EUVL status from Intel

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EUV infrastructure readiness snapshot: 0.33NA extension and 0.5NA

0.33NA Today	0.33NA Exten.	0.5NA	
Green	Yellow	Red	**EUV resist:** CAR capable for introduction. Stochastics driving process window for 0.33NA extension and 0.5NA. Need fundamental understanding of electron/ion/photon interaction with materials. Suppliers must have access to EUV photons and appropriate metrology.
Green	Yellow	Red	**EUV blank quality:** Capable for introduction. 0.33NA extension and 0.5NA require standards for front-side/back-side flatness, CTE, defectivity
Green	Yellow	Yellow	**Actinic Blank Inspection (ABI): 0.33NA**: Ready for qualification of HVM quality blanks at introduction. **0.5NA**: need to ensure metrology capability/timing
Green	Green	Green	**Mask pattern:** write capability for 0.33NA extension and 0.5NA – may need curvilinear
Green	Yellow	Yellow	**E-beam Mask Inspection: 0.33NA:** In use for low volume production. Need TPT increase
Green	Green	Yellow	**AIMS Mask Inspection: 0.33NA:** NXE:3400 illumination emulation underway; **0.5NA:** work needed
Yellow	Yellow	Red	**Pellicle: 0.33NA /0.5NA:** increased sensitivity to smaller defects. Improvement needed re. power resiliency, transmission, EUV-R, uniformity. Opportunity for industry participation.
Green	Green	Yellow	**Actinic Patterned Mask Inspection (APMI): 0.33NA/0.5NA:** Feature sizes drive need for actinic inspection in mask shop and fab.
Green	Green	Yellow	**Mask backside defect inspection / clean:** expect tighter requirements for mask backside contamination

- Green: Technical and commercial solution exists. Proof of concept demonstrated, HVM availability is eminent
- Yellow: Technical path exist. Proof of concept or Commercialization path needed
- Red: No technical path or requirements are unknown

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Conclusion

- Combined scanner/source availability continues to improve
  - Exposure source remains largest contributor to tool downtime
- Exposure source power meeting 250W roadmap and demonstrated in field systems
- Scanner defectivity levels improved with introduction of NXE:3400
  - Every system has demonstrated printable defects resulting from fall-on particles
  - Need remains for EUV pellicle and associated infrastructure / support
- Progress has been made in pellicle and membrane material development, but continued improvement necessary for increasing transmission, withstanding increased source power, and extending lifetime
- EUV AIMS system meeting expectations
- APMI operational for full mask inspection
- Next-generation considerations include material stochastics and thermal effects: recommend standards
- Need to consider stochastics for decreasing feature sizes and high NA: need to understand the interaction of EUV radiation with resist and design resist materials for stochastics

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- **11:00 AM ………………………. Session 2: EUV Masks**

  Ion Beam Technology Roadmap for EUV Mask Deposition and Absorber Etch Processes (Invited)

(P14) Sandeep Kohli, *Veeco Instruments*

- Current IBD platform has been qualified for 5 nm node
- For 3 nm and beyond focus on central wavelength uniformity and thickness control for reflectivity and particle control for yield
- Provided a roadmap for mask blank performance metrics – upgrade until 2022 for 5 nm node and then a new platform for 3 nm node
- Beyond 3 nm node CWL variation < 0.02nm and 0 defects >30 nm with > 50% yield. Efforts involve reconfiguration of source, target and fixture via modeling and inclusion of electrostatic traps. Reduce ion energy while maintaining the deposition rate
- Efforts on high-K absorber stack and att-PSM – deposition and etch. Ion bean deposition and etch for metal, binary metals and ternary metals. Have shown effective patterning for Ni, Pd or Pt

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- **11:00 AM .... Session 2: EUV Masks**
  Next Generation EUV Mask Blank Absorber Development (Invited) (P16)
  Vibhu Jindal, *Applied Materials*
- Listed deposition requirements – need single phase amorphous films
- Several material exist that give <2% reflectivity for <45 nm thickness. No damage with 50x cleans, good etch selectivity to Ru. Better NILS and contrast than TaN. Can be inspected with 193 nm and 266 nm. Defect repair work with Zeiss. Material being tested at SHARP and in a scanner
- Applied can engineer materials and provide an integrated solution (deposition, etch, clean, write, inspection etc.) with less than 2% reflectivity,
- EUV phase shift mask development. PSM with stack of absorbers that can provide 180 degree phase shift in <25 nm thickness.

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- **Selective and Directional Patterning of Ni for EUV Masks Application (Invited) (P11)**

  Jane P. Chang, *UCLA*

- Etching of Ni was confirmed on both blanket & patterned (trench & isolated line) samples, sidewall angles quantified on isolated line samples.
- RIE & ALE hybrid process tested on trench samples, better sidewall quantification to be performed on isolated line samples.

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- **Fabrication and Evaluation of SiN-based EUV Pellicle (Invited) (P12)** Jinho Ahn, *Hanyang University*

- Silicon nitride–based pellicles were successfully fabricated (83%, 81%)
- $MoSi_2$ is a good candidate for the emission layer (high EUVT and very low EUVR)
- Particles smaller than 10um does not affect mask imaging
- Particle contaminated pellicle shows less and slow heating during exposure
- Particles on the pellicle surface may not affect pellicle lifetime.

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- **Stochastic Failure Risk (Invited) (P13)** Kevin Lucas, *Synopsys*
- Reviewed a broad range of current continuous & stochastic simulation methods
- Compared continuous vs. stochastic process window (PW) error inputs
- Discussed a straight-forward extension of current PW budget methodologies to EUV compact stochastic PW modeling
  - With help from rigorous stochastic simulation analysis
- Provided examples of simulation flows for reducing stochastic failure risk by PW compact modeling analysis and mask synthesis
  - Standard ILS-based CD EUV failure risk increase
  - More accurate Optics + Resist stochastic EUV PW contour failure analysis

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- **Stochastic Investigation of the Impact of Absorber Variations on Wafer Patterns (Invited) (P15)**
  Derren Dunn, *IBM Research*
- PV band and stochastic PV band methods are inherently blind to interactions of OPC with mask process effects
- Strong dependence of failure relative frequency on OPC dissection and evaluation point strategies
- Retargeting to mitigate downstream unit process biases does not necessarily result in lower EUV hotspot relative frequency → need to consider carefully interaction of dissection and mask process interaction
- Interactions of local construct environments with retargeting, OPC dissection and targeting need to be considered carefully to minimize relative frequency of hotspots.
- Including mask process awareness and stochastic simulations in DTCO flow will enable finer grained design arcs → more competitive development design arc definition

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- **2:00 PM .... Session 3: EUV Resist**
- **EUV Resists: Can We Move Fast and Light? (Invited) (P34)** Anna Lio, *Intel Corporation*
- EUV is in HVM. Roadmaps extend well into the future with High NA. Photoresist is central to current and future EUVL success
- Today's resists should be further optimized to bridge the gap with High NA. No chemistry today can support the full range of applications planned for EUVL long term – New Chemistries are needed for long term EUV success. They need to be tunable and provide stochastic control
- Photoresist development needs to be "Fast and Light" to keep us on track and accelerate the rate of improvement beyond historical trends. This can be achieved by focusing on Fundamentals, using our collective knowledge and expertise, careful planning to control risk
- This needs support from everyone – academia, government and industry- including adequate funding

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- **2:00 PM .... Session 3: EUV Resist**
- **Multi-Trigger Resist (Invited) (P33)**
  Alex Robinson, *Irresistible Materials & Univ. of Birmingham*
- IM are developing new resist material for EUV lithography
- **Multi-Trigger chemistry enhances chemical gradient without quenchers**
- Small formulation changes can change resist performance significantly
- Film thickness impacts dose, LER, LWR and pattern collapse
- Improved thermal stability leads to increased cross-linking which lowers LWR, top loss, collapse
- **Adding non metallic high-Z element to crosslinker to improves resolution and LWR and enables higher aspect ratio. Investigating whether due to chemistry or material changes take place.**
- Introducing new element of MTR tuning by using unprotected phenols, can modulate speed of resist

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- **Role of Ambient Conditions on Organotin Cluster Based Extreme Ultraviolet Resist Chemistries (P35)**
  Gregory S. Herman, *Oregon State University*

- Low kinetic energy electrons (E_{kin} = 80 eV) are effective for simulating EUV radiation chemistries.

- Temperatures above 400 °C are required to desorb butyl groups, suggesting good thermal stability during EUV exposures and bake steps.

- Presence of oxygen increases cross sections and rate of BuSn homolytic cleavage of Sn-C bond.

- Contrast curves and AP-XPS results suggest that radical hydrogen abstraction and radical - radical coupling reactions result in polymerization of organotin species.

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- **3:30 PM ……………………… Session 4: EUV Optics and Patterning**
- **Optics for EUV Lithography (Invited) (P24)** Sascha Migura, Carl Zeiss SMT GmbH, Germany

- TODAY - The Starlith® 3400 for the NXE:3400B
- Multiple systems shipped.
- ZEISS is fully committed and ready for high volume ramp-up.

- TOMORROW - High-NA with the Starlith® 5000 for the EXE:5000
- Enables further shrink for the semiconductor industry to continue Moore's Law.
- Design has been finalized; mirror production has started.
- Fast infrastructure and equipment build-up at ZEISS.

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- **3:30 PM .... Session 4: EUV Optics and Patterning**
- **Defectivity Improvements Enabling HVM for EUV Scanners (P23)** Mark van de Kerkhof, *ASML*

- Reticle frontside most critical as yield impact is largest
  ultimate requirement: ~1 particle (>32nm) per month
- We are continuously and aggressively improving defectivity performance through breaking the defect generation chain by
    - Improved cleanliness of system
    - Improved flushing
    - Protective (cross-)flows
    - Tune the EUV-induced plasma (gas pressure, gas composition, dynamics)

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- **Update on EUV Optics Calibration (Tentative title) (P21)** Eric Gullikson, *CXRO*

- Prior to the 70's x-ray optics = grazing incidence
- In 1981 - Imaging with a normal incidence x-ray mirror was introduced
- 1980's saw the renaissance of x-ray optics
- BL 6.3.2 achieves the highest accuracy for EUV reflectivity measurements as Demonstrated by international reflectometry round-robins. BL 6.3.2 has played an important role in the development of EUVL over the past 25 years
- Scattering is determined by substrate roughness
- Measurements of EUV optical constants of mask relevant materials
- Development of narrow bandwidth mirrors and Multilayers for the water window (2.3 – 4.4 nm)
- X-Ray Interactions with Matter website. The atomic scattering factors are revised as new measurements are available

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- **Maskless, High-NA EUV Scanner (P22)** Kenneth C. Johnson, *KJ Innovation*

  Maskless EUVL at 13.5 nm, 0.55 NA could be implemented with existing technology infrastructure, and relative to HVM mask-projection EUVL would have:

  - ≈100X lower throughput, but …
  - ≈100X lower power requirement
  - ≈10X higher exposure dose
  - ≈1000X lower scan velocity, acceleration
  - Maskless capability

  For Blue-X (6.7-nm , 0.55-NA) Maskless EUVL could overcome some critical feasibility limitations of HVM mask-projection including:

  - Power (≈10X reduced ML mirror bandwidth at 6.7 nm vs 13.5 nm)
  - Stochastics (2X smaller dimensions with 2X higher photon energy)
  - Mask 3-D effects (≈200 ML bilayers)

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- **Overview, Status and Performance of the 0.5-NA EUV Microfield Exposure Tool at Berkeley Lab (P25)**
  Chris Anderson, *CXRO*
- OVERVIEW STATUS AND PERFORMANCE OF THE 0.5-NA EUV MET AT BERKELEY LAB

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- **8:30 AM Keynote II**
- **EUV Lithography Research and Development Activities in Japan (Keynote Presentation) (P4)**

Takeo Watanabe, University of Hyogo

- Overview of current EUVL R&D projects in Japan and R&D capabilities at University of Hyogo
- The Resonant soft X-ray scattering method is very powerful method to evaluate the origin of resist stochastic and layer analysis in an EUV resist film. Univ. Hyogo offers capabilities in this area. Described the technology and presented several results.
- Results of study of interaction of H2 gas with ML.
- Study of Out of band reflectance spectra of the Mo/Si ML and absorber
- Pros and Cons of EUVL extension are discussed. At 6.x FEL may be necessary

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- **Enabling the Semiconductor Roadmap from a Multi-Angled Approach (Keynote Presentation) (P3)**

  Steven Welch*, Applied Materials*

- Semiconductor scaling and enablers for Moore's law beyond 5 nm node
  - Power, performance and area cost scaling per Moore's Law have been scaled by 2-D scaling and materials
  - New additions are – New architecture, 3D, new ways to shrink and advanced packaging.
- Logic scaling advancements
  - New metal gates and new contact fills. Gate structure moves from FinFET to horizontal GAA (Samsung in 2021), as they allow increased current per unit area. Challenges are parasitic capacitance reduction between sheets and metal-gate Vt tuning in narrow gates
- Memory advancements to scale AI big data.
- Examples of how CMOS scaling will look at 3 nm, 2 nm and beyond. In addition to new geometry and designs, they will be enabled by selective deposition and selective removal.
- Outlined scaling opportunities in the backend via new materials (replacing Cu with Co, Ru or Mo) and interface management. New memories will be enabled by new designs, 3D architecture and new materials.
- Analog memories are possible in future for machine learning accelerator. He also sees analog computing in the future, which will require further advances in process variability.

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- **10:20 AM……………………..Session 7: EUV Sources**
- **Challenge of High Power LPP-EUV Source with Long Collector Mirror Lifetime for Semiconductor HVM (Invited) (P44)** Hakaru Mizoguchi, *Gigaphoton Inc.*

- High conversion efficiency 4.5% is realized with Pre-pulse technology.
- High speed (>90m/s) & small (20micron) droplet is realized.
- Gigaphoton redefined power target to ≧330W ave. with -0.05%/Gpls, >90% availability
- CO_2 laser power upgrade >27kW is successfully demonstrated.
- CE enhancement condition >6% is clarified through small experimental device by Tomson scattering measurement.

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- **10:20 AM……………………..Session 7: EUV Sources**
- **Lithography Machine In-line Broadband Spectrum Metrology and Feedback-control System (P43)**

  Fei Liu, *ASML*

- *Proposed using in-band spectrum to control the scanner*
- Source plasma emission spectrum is highly relevant for system performance
- Using DGL membrane to eliminate DUV and IR at wafer level has an impact on EUV transmission
- Using spectrum measured at source for feedback control has limitations (unknown angular dependency, unknown clipping at IF, collector impact, etc)
- It is advantageous to implement in-line broadband spectrum metrology and control system in the scanner

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- **Energetiq Source Update (Tentative Title) (Invited) (P46)** Toru Fujinami, *Energetiq*
- The cause of the instability for pure Xenon is plausibly identified as a “unipolar arc”, due to the voltage between back side of the pinch and wall.
- The instability has two characteristics
    - Position : immediately behind the bore
        - Voltage from plasma to wall is highest
    - Power
        - The arc steals power from the pinch , which makes lower energy pulse.
- Helium suppresses the instability described above.

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- **Adlyte Corporation – Source Update (Tentative Title) (Invited) (P42)** Fariba Abhari, *Adlyte Corporation*
- Presented recent progress
    - Continuous source operation of up to 35 hours demonstrated
    - Major improvements relating to thermal management of the source for long term operation and Sn recovery
    - Developed and demonstrated Pre- pulse conditioning droplet capability
    - A 2X reduction in the foot print and the volume

- Roadmap
    - Incorporated capability for hot swap in HVM
    - Integrated load locks assembly including quick connect components to maintain thermal conditions and increase uptime
    - Set up specialized droplet assembly testing and calibrations and 24 by 7 operational capability
    - Integrate packaging to allow us to run system for one month without refill and Optimize CoO for range of applications

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- **EUV Metrology with a Compact Accelerator-based Source (Invited) (P41)** Yasin Ekinci, *PSI*
- COSAMI design philosophy:
    - Go for proven concepts and well-established technologies
    - Minimum delivery time by avoiding R&D and prototyping
    - Compact design without compromising performance
    - High-reliability as a production tool
    - Ensuring radiation safety standards in production environment

- COSAMI Design specifications
    - Clean EUV power: >100 mW
    - Tunable EUV wavelength
    - High brightness: > 1GW/mm^2.std
    - High intensity stability: 0.1%
    - High reliability: up time > 99%
    - Minimum maintenance: <5%

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- **High Repetition Rate (81.25MHz) FEL Project Based on cERL (P45)** Hiroshi Kawata, *KEK*
- *Currently working on mid-IR compact FEL for 1- 100 W. This learning will benefit development of EUV – FEL (aim of 10 kW)*

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- **1:40 PM .... Session 8: Blue-X I**
- **Blue-X: the New Frontier (P58)**

Vivek Bakshi, *EUV Litho, Inc.*

- Community Response has been very positive
  - Two sessions each in 2018 Source Workshop and 2019 EUVL Workshop
- Due to work for last few years, 6.x ML peak reflectivity can be >70% (Univ. Twente).
- Combining 6.x nm ML with BAT lasers, we already have a potential Blue-X solution for extension of EUVL!
- Newer optical designs are possible for scanner (fewer reflections) but they will allow LIMITED patterning options. What are the new possibilities?
  - Reduction of peak reflectivity from 0.7 to 0.4 will require reflections to go from 11 to 5 for the same throughput.
- Good to note that some of these new developments will also can be applicable at 13.5 nm – BAT lasers, ML improvement and new optical designs

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- **1:40 PM ……………………………. Session 8: Blue-X I**
- **Thulium-based EUV Drive Lasers Scalable to Near-MW Average Powers (Invited) (P51)**

C.W. Siders, *Lawrence Livermore National Laboratory*

- We have developed a 100-kW BAT point design tailored for EUV application. Design scalable to even higher powers, but unclear if target supports. Steady-state diode pumping allows for very high pulse-to-pulse energy stability. Flexible and robust pulse shaping. Pre- and main-pulse in common amplifier
- System-level CE, exposure, and cost trade study will layout development paths:
- Large-scale ensemble modeling of:
  - target model for CE and other important features (next talk)
  - Hydrodynamic (ALEAMR) model of droplet-to-droplet interaction
- Laser system modeling and optimization around ensemble optimal performance
- In parallel, key risk-mitigation and reduction to practice of laser technology

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- **An Optimization Study of EUV Sources driven by Lasers of Different Wavelengths (Invited) (P53)**

  Howard Scott, *Lawrence Livermore National Laboratory*

- The highest CE seen in ensembles run so far is 3.3% for thulium and 4.4% for CO_2. Further optimization is in progress.
- CO_2 driven experiments have delivered a ~7% CE. The simulated and experimental CEs are close enough to indicate that tin vapor targets are relevant.
- The best thulium run has a higher total EUV exposure than the best CO2 run.

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- **Effect of Laser Wavelength on EUV Plasma Dynamics, Source Efficiency, and Ionic Debris Evolution (Invited) (P56)** Tatyana Sizyuk, *Purdue University*

- Modeling of Sn LPP with 2 micron lasers
  - CE is similar to one obtained for 1 micron drive lasers
    - Previous Modeling shows that CE is higher for 1 micron drive lasers than for 10 micron CO2 lasers
  - Videos of Sn LPP evolution with 2 micron lasers

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- **3:10 PM .... Session 9: Blue-X II**
- **Advanced Multilayer Development for the Water-Window Spectral Region (Invited) (P52)** F. Delmotte, Universite Paris-Saclay

- Peak ML reflectivity is 23% at 3.1 nm – which is the highest value published so far
- To increase the peak reflectivity (31% from modeling) – need to decrease the period drift < 0.01 nm per period, increase the number of periods, Optimize CrN, B_4C and Sc thicknesses
- For this we need: Accurate (= experimental) values for CrN refractive index and Analysis techniques with sub-nanometer resolution -> interface properties, N_2 profile

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- **Refractive index measurements with improved accuracy around EUV/x-ray absorption edges and impact in multilayer modeling (Invited) (P54)** Regina Soufli, *Lawrence Livermore National Laboratory*

- Refractive index is not accurately known in EUV / x-ray region
- We have developed optimized methodologies to measure refractive index of Cr, Pt and W with improved accuracy near M- N- and O- edges.
- More materials need measurements – accurate refractive index values will enable the design of EUV components with maximized performance

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- **Adaptation of the Reflectance of Bragg Mirrors to Wide Source Spectra (Invited) (P57)** R. Meisels, Institute of Physics (Austria)

- Depth graded mirrors can be used to improve broad –reflectivity at 13.5 nm, 6.5 nm and 3.12 nm

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- **Characterization of laser-produced plasmas in the 1-6 nm region using cryogenic Xe targets (P55)**
  S.C. Bott-Suzuki, University of California San Diego

- The CE measurements are the first for Xe in 1-6nm range. Absolute CE at 6nm (~200eV) is about 1%. For short wavelengths (1.4nm, 870eV) the best observed CE~0.08%

- No strong effect of laser pulse length (intensity) at the same configuration (130ps vs 600ps). Maximum conversion efficiency requires >100mJ on target

- Slit imager reports accurate dimensions of the emitting plasma directly, and is simple to implement and analyze
- Emission spot sizes <20mm observed

- The fits to the low energy ion spectra looks like a useful way to infer plasma temperature. The fitted temperatures scale as expected with laser energy and focal position. Ion spectrum extends to very high energy (>100keV) but yield dominated by low energy (<1keV). High energy tail strongly dependent on laser parameters

- Use of fitted temperatures from FC may allow recovery of density of the emitting plasma through spectral fitting