EUREKA: A Industry EUV Research Center at LBNL

Patrick Naulleau

Center for X-ray Optics

Lawrence Berkeley National Laboratory
Outline

• Reflectometry
• Mask review: SHARP
• 0.3-NA MicroExposure: MET3
• 0.5-NA MicroExposure: MET5
• Other
Cornerstone tools

Reflectometer/Scatterometer

EUV AIMS up to 0.6 NA

0.3-NA Litho

0.5-NA Litho coming soon

13-nm in non-CAR
Specifications

- Wavelength precision: 0.007%
- Wavelength accuracy: 0.013%
- Reflectance precision: 0.08%
- Reflectance accuracy: 0.08%
- Spectral purity: 99.98%
- Dynamic range: $10^{10}$
High accuracy measurements of optical constants of EUV resist and mask materials

PMMA ($\lambda=13.5$ nm)

$\delta=0.0242$, $\beta=0.0054$

d = 286.5 nm

Reflectance vs. Angle (deg)
High accuracy measurements of optical constants of EUV resist and mask materials

TaN (\(\lambda=13.5\) nm)

\[ \delta = 0.0577 \]
\[ \beta = 0.03365 \]
\[ d = 30.4\) nm \]
\[ \sigma = 0.6\) nm \]
Diffraction characterization of EUV masks

![Graph showing diffraction efficiency vs. angle for a 500 nm period](image)

E. Gullikson
EUV High NA review tool

- **Optics:**
  - Zoneplate-lenses

- **Effective NA:**
  - 0.250–0.625

- **Coherence:**
  - Programmable

- **Magnification:**
  - Variable

- **Imaging modes:**
  - Bright, Dark, Zernike phase, DIC …
Leverage CXRO world-leading zoneplate fabrication capabilities
Select between hundreds of lenses on the fly
0.625 effective NA demonstrated

16-nm code lines (64-nm on mask)

M. Benk, K. Goldberg, A. Wojdyla
Freeform source capabilities

Target source shape

Measured source shape
SHARP true to wafer print

Mask SEM

SHARP EUV

Wafer SEM
Quantitative phase

Resolving SRAFS

$I$ $\Phi$

200 nm

20°
Anamorphic NA capabilities
EUV 0.3-NA MET
MET: engine for materials learning

Cumulative wafers

Cumulative materials
13-nm patterning achieved in non-CA resist

LWR = 3.1 nm
7x throughput gain on 25-nm contacts with PSM mask

Etched-ML mask

Checker PSM

Absorber

13 mJ/cm²

94 mJ/cm²
• NA = 0.5
• Magnification = 5x
• Resolution limit = 8 nm
• Programmable pupil fill
• Mask angle of incidence = 6°
• Integrated wavefront metrology
• Robotic linked track
Reticle stage assembly

Projection optics box

Tool core metrology frame

Wafer stage assembly
# 7-axis reticle stage

<table>
<thead>
<tr>
<th></th>
<th>Spec</th>
<th>Measured</th>
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<tbody>
<tr>
<td>XY Low freq. (&lt;2Hz) PV</td>
<td>3 nm</td>
<td>0.92 nm</td>
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<tr>
<td>XY High freq. (&gt;0.5Hz) RMS</td>
<td>2 nm</td>
<td>0.33 nm</td>
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<tr>
<td>Z Low freq. (&lt;2Hz) PV</td>
<td>10 nm</td>
<td>1.7 nm</td>
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<tr>
<td>Z High freq. (&gt;0.5Hz) RMS</td>
<td>3 nm</td>
<td>0.61 nm</td>
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## 5-axis wafer stage/2-axis LSI carriage

<table>
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<th>Measured</th>
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<tr>
<td>XY Low freq. (&lt;2Hz) PV</td>
<td>3 nm</td>
<td>0.51 nm</td>
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<tr>
<td>XY High freq. (&gt;0.5Hz) RMS</td>
<td>1 nm</td>
<td>0.65 nm</td>
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<tr>
<td>Tip/Tilt RMS</td>
<td>18 mrad</td>
<td>0.15 mrad</td>
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<tr>
<td>Z Low freq. (&lt;2Hz) PV</td>
<td>10 nm</td>
<td>1.5 nm</td>
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<tr>
<td>Z High freq. (&gt;0.5Hz) RMS</td>
<td>3 nm</td>
<td>0.42 nm</td>
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### M1

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<th>Range</th>
<th>Specification</th>
<th>Result</th>
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<tbody>
<tr>
<td>Figure</td>
<td>CA – 3mm</td>
<td>&lt; 0.1nm rms</td>
<td>0.04 nm rms</td>
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<tr>
<td>Flare</td>
<td>3mm – 0.43um</td>
<td>&lt; 0.17nm rms</td>
<td>0.12 nm rms</td>
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<tr>
<td>HSFR</td>
<td>1um – 10nm</td>
<td>&lt; 0.15nm rms</td>
<td>0.08 nm rms</td>
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### M2

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<th>Result</th>
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<tr>
<td>Figure</td>
<td>CA – 8mm</td>
<td>&lt; 0.1nm rms</td>
<td>0.08 nm rms</td>
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<tr>
<td>Flare</td>
<td>8mm – 1.2um</td>
<td>&lt; 0.17nm rms</td>
<td>0.14 nm rms</td>
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<tr>
<td>HSFR</td>
<td>1um – 10nm</td>
<td>&lt; 0.15nm rms</td>
<td>0.09 nm rms</td>
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</tbody>
</table>

**Predicted POB EUV flare = 2.86%**
**System wavefront 2x better than spec**

<table>
<thead>
<tr>
<th>Reticle field point (um)</th>
<th>WFE @ 30cycles across aperture (nm rms)</th>
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</thead>
<tbody>
<tr>
<td>0, 0</td>
<td>0.21 (spec=0.5)</td>
</tr>
<tr>
<td>75, 500</td>
<td>0.43 (spec=1.0)</td>
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<tr>
<td>75, -500</td>
<td>0.41 (spec=1.0)</td>
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<tr>
<td>-75, -500</td>
<td>0.34 (spec=1.0)</td>
</tr>
<tr>
<td>-75, 500</td>
<td>0.36 (spec=1.0)</td>
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</table>
Platform integration nearly complete
Potential expansion of EUREKA program resources
Instrumentation for direct characterization of EUV radiation chemistry

1: Introduce materials as molecular or nanoparticle beam
2: Irradiate with EUV or electrons
3: Measurement of electrons and chemistry

- Nebulized polymeric resist condenses to particles
- Inorganic nanoparticle resists coated in-situ with resist materials
- Molecular resist
- EUV
- Photo-electron imaging for energy and count

- Count
- Electron Energy
- Mass spectroscopy for molecular reactions

$e^- = 92\text{ eV}$

$E_e = \text{Binding E}$
RSoXS: soft-x-ray potential for 3D chemically sensitive profile metrology

CD-RSoXS on Polymer Lithography Grating

Sunday et al. JM3 12 (3), 2013, 031103

Compares favorably to hard X-ray and provides benefit of chemical sensitivity for potential use in latent images

A. Hexemer
Realtime in liquid AFM for development studies

Encased cantilever for fast response in liquid

Start of developer injection
Acknowledgements

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Eric Gullikson, LBNL
Ryan Miyakawa, LBNL
Seno Rekawa, LBNL
Antoine Wojdyla, LBNL