Fabrication of EUVL Micro-field Exposure Tools with 0.5 NA

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Outline

- Introduction
  - Application
  - Design considerations
- Mirror Fabrication
  - Component testing
  - EUV fabrication / development / CCOS and IBF
  - Component fabrication results
    - Figure, MSFR, HSFR ranges
- Opto-mechanical assembly and alignment
  - Assembly process
  - Alignment performance
- Coating
- Final transmitted wavefront performance
- Summary
ZYGO corporation got contracted to build several EUV-L Micro-Field Exposure Tools with 0.5NA, known as MET5.

- Those tools are used for infrastructure development required for the EUV lithography industry to support printing at the ~12nm node and below.
  - Example: resist development.
- The lithography industry drive to print smaller feature sizes requires a shift towards smaller wavelengths and higher NA... and ultimately to tighter optical surface specifications.

**Design Features:**
- Modified Schwarzschild Design
- 13.5nm wavelength
- 0.5NA
- 5X reduction
- Field dimension 30 x 200 microns

Reticle plane tilted by 6 degrees.
- Reticle (Mask) used in reflection at EUV wavelengths

**Performance Requirements:**
- Diffraction limited Imaging with 
  - Transmitted wavefront error:
    - Center of the field < 0.5nm RMS
    - Edge of the field < 1.0nm RMS
    - And Flare < 5%

This is an upgrade to existing 0.3NA tools. Fitting the PO in existing platform volume is a design and manufacturing challenge.
Mirror Fabrication

- ZYGO Extreme Precision Optics (EPO) group in Richmond, California is a leader in optical surfacing development.
  - 40 years of Computer Controlled Optical Surfacing (CCOS) use and development.
  - Over 15 years of Ion Beam Figuring (IBF) experience.
  - Over 20 years of EUV optics fabrication.
  - During that period, EUV optics specs got tighter by a factor of 5
    - For all Ranges: Figure, MSFR, and HSFR

- The M1 and M2 Mirrors are fabricated using a combination of conventional and discrete computer controlled polishing techniques.
  - Aspheric departures of 46 and 51 microns.
  - Aspheric slopes of 8.6 microns/mm and 3.6 microns/mm
Mirror Metrology

• Figure Metrology
  – Custom built, full aperture test station
  – Zygo Verifire™ MST
  – High precision computer generated holograms (CGH’s)
  – **Reproducibility of 20pm RMS**
    • Including mount deformations
  – **Total Accuracy of both tests < 0.2nm RMS**
    • Verified when first POB assembly was tested in our POB system test.

• Full Spatial Range of metrology instruments
  – Figure test station
  – SASHIMI (custom built sub-aperture interferometer)
  – Optical Profilometer
    • 2.5x and 50x objectives
  – Atomic Force Microscope (AFM)
Mirror Fabrication Results

- Average achieved RMS for 3 sets of mirrors (i.e. 3 complete systems)

<table>
<thead>
<tr>
<th>M1 mirror</th>
<th>Ranges</th>
<th>MSFR</th>
<th>HSFR</th>
<th>Entire range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CA - 3mm</td>
<td>3mm to 0.43μm</td>
<td>1μm - 10nm</td>
<td>CA - 10nm</td>
</tr>
<tr>
<td>Results</td>
<td>0.050 nm RMS</td>
<td>0.128 nm RMS</td>
<td>0.088 nm RMS</td>
<td>0.163 nm RMS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>M2 mirror</th>
<th>Ranges</th>
<th>MSFR</th>
<th>HSFR</th>
<th>Entire range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CA - 8mm</td>
<td>8mm to 1.2μm</td>
<td>1μm - 10nm</td>
<td>CA - 10nm</td>
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<tr>
<td>Results</td>
<td>0.066 nm RMS</td>
<td>0.123 nm RMS</td>
<td>0.085 nm RMS</td>
<td>0.163 nm RMS</td>
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</table>

- The MSFR and HSFR are evaluated by stitching the PSD curves from multiple metrology instruments and integrating under the curve.

- **Average Achieved Flare** is: **2.75%** *(spec is 5%)*

- System Flare is calculated as total integrated scatter (TIS) from the MSFR range surface error.

*The PSD’s of various instruments are combined to get an integrated PSD for the entire surface*

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**Figure MSFR HSFR Entire range**

**Ranges**

- CA - 3mm
- 3mm to 0.43μm
- 1μm - 10nm
- CA - 10nm

**Results**

- 0.050 nm RMS
- 0.128 nm RMS
- 0.088 nm RMS
- 0.163 nm RMS

**Figure MSFR HSFR Entire range**

**Ranges**

- CA - 8mm
- 8mm to 1.2μm
- 1μm - 10nm
- CA - 10nm

**Results**

- 0.066 nm RMS
- 0.123 nm RMS
- 0.085 nm RMS
- 0.163 nm RMS
Opto-Mechanical Assembly and Alignment

• The POB structure is super Invar to match the low expansion material of the mirrors.

• The bipod flexures rigidly constrain the mirror positions, while allowing low force and moments, required to achieve low distortion of the optical surface.

• The POB alignment is performed with the hexapod legs and a software control system.

• Initial POB assembly is done with a Coordinate Measuring Machine (CMM) in order to achieve initial alignment within the range of the hexapod legs.
  – Hexapod legs have super high accuracy (5nm) but limited range (100 microns)
  – CMM process yields wavefront errors <50nm RMS that can be corrected by using less than 30 microns of hexapod leg adjustment.
Opto-Mechanical Assembly and Alignment

- The *internally developed* Hexapod Control software seamlessly converts wavefront data to mirror adjustments and finally to hexapod leg moves to adjust the wavefront.

- The move executes in approximately 2 minutes with an M1 mirror position accuracy of 10nm laterally and 10nm axially.
  - All 6 hexapod legs must move in a coordinated fashion even for the simplest motion of the M1 mirror.

*POB initial alignment sequence shows the WFE improving from 52nm RMS to approximately 1 nm RMS in only one adjustment cycle.*
- Synthetic fringes shown, with wavefront map shown in lower right frame
EUV Multilayer Coating

- The mirrors are coated at Lawrence Livermore National Laboratory (LLNL) with a graded EUV multilayer.
- The Mo/Si multilayers are optimized to maximize reflectivity while minimizing resulting coating stress on the optic.
- The Mo/Si coatings were measured at the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory (LBNL).

**Table of Coating Specifications and Achievements**

<table>
<thead>
<tr>
<th>Coating Metric</th>
<th>Spec</th>
<th>Achieved</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Transmission</td>
<td>&gt;= 25%</td>
<td>&gt; 30% ✓</td>
<td>ALS Reflectivity measurement</td>
</tr>
<tr>
<td>Centroid wavelength</td>
<td>13.50nm +/- 0.05nm</td>
<td>13.5 ✓</td>
<td>ALS Measurement</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Goal &gt;= 0.5nm</td>
<td>0.59nm FWHM ✓</td>
<td>ALS Measurement</td>
</tr>
<tr>
<td>Added Figure Error</td>
<td>Goal &lt; 0.1nm RMS</td>
<td>0.1nm RMS ✓</td>
<td>System Wavefront Test</td>
</tr>
</tbody>
</table>

Modeled reflectivity curves for individual mirror and system
Final Transmitted Wavefront performance

- The measured transmitted wavefront error of the 3 POBs is $< 0.25\text{nm RMS}$.
  - This is less than half of the specification !!!

### Final Single Pass Transmitted Wavefront Error

<table>
<thead>
<tr>
<th>POB</th>
<th>RMS Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>POB 1</td>
<td>0.24nm</td>
</tr>
<tr>
<td>POB 2</td>
<td>0.24nm</td>
</tr>
<tr>
<td>POB 3</td>
<td>0.21nm</td>
</tr>
</tbody>
</table>

### 37 Term Zernike Fit of Transmitted Wavefront Error

<table>
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<tr>
<th>POB</th>
<th>RMS Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>POB 1</td>
<td>0.18nm</td>
</tr>
<tr>
<td>POB 2</td>
<td>0.22nm</td>
</tr>
<tr>
<td>POB 3</td>
<td>0.18nm</td>
</tr>
</tbody>
</table>

The Final Projection Optics system ready for integration in a vacuum system.
The POB system wavefront metrology is performed with a Zygo Verifire™ MST, at visible wavelength.

The measured wavefront RMS has reproducibility of better than 10 picometers.

<table>
<thead>
<tr>
<th>Test Iteration</th>
<th>WFE (nm RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>0.212</td>
</tr>
<tr>
<td>Test 2</td>
<td>0.216</td>
</tr>
<tr>
<td>Test 3</td>
<td>0.214</td>
</tr>
<tr>
<td>Test 4</td>
<td>0.212</td>
</tr>
<tr>
<td>Test 5</td>
<td>0.214</td>
</tr>
<tr>
<td>Test 6</td>
<td>0.211</td>
</tr>
<tr>
<td>Test 7</td>
<td>0.212</td>
</tr>
<tr>
<td>Test 8</td>
<td>0.218</td>
</tr>
<tr>
<td>Average</td>
<td>0.214</td>
</tr>
<tr>
<td>RMS deviation</td>
<td>0.0002</td>
</tr>
<tr>
<td>P-V deviation</td>
<td>0.0007</td>
</tr>
</tbody>
</table>
Final Transmitted Wavefront performance

- Wavefront error over the field.
  - 0.15mm x 1.0mm field at the reticle (object side)
  - 30 x 200 microns at wafer

- Largest Wavefront error over the field is 0.48nm RMS for all 3 POB’s.
  → Less than half of the spec!!!

- Field aberrations include: astigmatism, field curvature and spherical aberration.
  - The Field aberrations are prescribed by the nominal optical design

Largest WFE over the field of all 3 POB’s
Final Transmitted Wavefront performance

• Due to the excellent wavefront performance achieved, the usable field dimension that meets the specification can be increased.
  – Allows the customer to use a larger area for their printing tests.

• The increase in the useable area is 8x.
  – From $0.15\text{mm}^2$ (0.15mm x 1.0mm)
  – To $1.3\text{mm}^2$ (0.85mm x 1.8mm)
The fabrication of three 0.5NA EUV small field micro-exposure tools (MET) is complete. The results of all 3 systems are extremely good:

- The achieved single pass transmitted wavefront of 0.21 to 0.24nm RMS is less than half of the 0.5nm specification at the center of the field.
- The maximum measured single pass transmitted wavefront across the specified field is 0.48nm RMS, less than the 1.0nm specification.
  - This indicates that the dimension of the usable field may be larger than the 0.15mm x 1.00mm specified field dimension by up to 8 times.
- The MSFR and HSFR are well in spec.
- The average achieved flare of 2.75% is close to half of the 5% specification
- The component test accuracy was confirmed by the POB system test measurement of the first assembly.
- The assembly process that was developed produces POBs that are close to final alignment and the resulting POB assemblies have the conjugates near their target positions.
- The POB system test reproducibility is at the picometers level