Optics Manufacturing at the sub-nm level a.k.a. Fabrication of EUVL Micro-field Exposure Tools with 0.5 NA

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  – Design considerations

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• Opto-mechanical assembly and alignment
  – Assembly process
  – Alignment performance

• Final transmitted wavefront performance

• Summary
Introduction

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 200microns
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
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

Technologies used in fabrication of the EUV optics for the MET5 Projection Optic Box

Extremely high for EUV optics
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></th>
<th>Figure</th>
<th>MSFR</th>
<th>HSFR</th>
<th>Entire range</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 mirror</td>
<td>Ranges</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CA - 3mm</td>
<td>3mm to 0.43µm</td>
<td>1µm - 10nm</td>
<td>CA - 10nm</td>
</tr>
<tr>
<td></td>
<td>Results</td>
<td>0.050 nm RMS</td>
<td>0.128 nm RMS</td>
<td>0.088 nm RMS</td>
</tr>
<tr>
<td>M2 mirror</td>
<td>Ranges</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CA - 8mm</td>
<td>8mm to 1.2µm</td>
<td>1µm - 10nm</td>
<td>CA - 10nm</td>
</tr>
<tr>
<td></td>
<td>Results</td>
<td>0.066 nm RMS</td>
<td>0.123 nm RMS</td>
<td>0.085 nm RMS</td>
</tr>
</tbody>
</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**
Opto-Mechanical Assembly and Alignment

- 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.

- 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.
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.
Final Transmitted Wavefront performance

• The measured transmitted wavefront error of the 3 POBs is < 0.25nm RMS.
  – This is less than half of the specification !!!

**Final Single Pass Transmitted Wavefront Error**

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

**37 Term Zernike Fit of Transmitted Wavefront Error**

<table>
<thead>
<tr>
<th>POB 1</th>
<th>POB 2</th>
<th>POB 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.18nm RMS</td>
<td>0.22nm RMS</td>
<td>0.18nm RMS</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 test station is computer controlled allowing remote operation, and capable of running automatic measurements.

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><strong>Average</strong></td>
<td><strong>0.214</strong></td>
</tr>
<tr>
<td><strong>RMS deviation</strong></td>
<td><strong>0.002</strong></td>
</tr>
<tr>
<td><strong>P-V deviation</strong></td>
<td><strong>0.007</strong></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.
  \(\rightarrow\) 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
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 approximately 8x.
  – From 0.15mm$^2$ (0.15mm x 1.0mm)
  – To 1.3mm$^2$ (0.85mm x 1.8mm)
Summary

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
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