Multilayer Collector Optics for Water Window Microscopy

2015 International Workshop on EUV and soft X-Ray Sources

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Dublin, November 11, 2015
Outline

- Introduction
- EUV multilayer optics activities
- Microscopy in the water window
- Summary
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History of optiX fab.

1997: Start of EUV multilayer development @ Fraunhofer IOF
2000: First paper at SPIE “Microlithography” on Mo/Si multilayer mirrors
2002: Start of cooperation with semiconductor industry:
       ASML, Cymer, Intel, Jenoptik, Schott Lithotec, Zeiss, etc.
2009: Coating of first NXE:3100 collector mirror
2011: Development of collector refurbishment technologies
History of optiX fab.

1997: Start of EUV multilayer development @ Fraunhofer IOF
2000: First paper at SPIE “Microlithography” on Mo/Si multilayer mirrors
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       ASML, Cymer, Intel, Jenoptik, Schott Lithotec, Zeiss, etc.
2009: Coating of first NXE:3100 collector mirror
2011: Development of collector refurbishment technologies

2012: Foundation of Fraunhofer IOF spin-off company optiX fab.
2013: August 1st: Operations start @ optiX fab.
Nov 11, 2015: Delivery of 3708 EUV and X-ray mirrors to customers
optiX fab. organization

- **Mission:** Fabrication of customized EUV optics and optical components for EUV lithography @ 13.5 nm, for EUV, soft and hard X-ray applications, synchrotron and FEL beamlines, metrology, R&D, HHG sources, etc.

- **Address:** optiX fab GmbH
  Hans-Knöll-Str. 6
  D - 07745 Jena

- **URL:** www.optixfab.com

- **Team:**

  - Torsten Feigl
  - Marco Perske
  - Hagen Pauer
  - Tobias Fiedler
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Multilayers for 13.5 nm

\[ R = 70.12 \% \]
\[ \lambda = 13.48 \text{ nm} \]
\[ \text{FWHM} = 0.528 \text{ nm} \]
\[ \text{AOI} = 5 \text{ deg.} \]

Measured @PTB Berlin
Broadband Multilayers for 12.5 ... 16.0 nm

\[ R \sim 20\% \]
\[ \lambda = 12.5 \ldots 16.0 \text{ nm} \]
\[ \text{FWHM} = 3.86 \text{ nm} \]
\[ \text{AOI} = 30 \text{ deg.} \]

Measured @PTB Berlin
Beamsplitters for 13.5 nm

\[ R = 29.0 \% \]
\[ T = 21.5 \% \]
\[ \lambda = 13.5 \text{ nm} \]
\[ \text{AOI} = 45 \text{ deg.} \]

Measured @PTB Berlin
Multilayers for the water window

Reflectivity in water window region (s-pol @ AOI = 1.5deg)

Measured @ PTB Berlin
### Multilayers for 8 ... 12 nm

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>AOI (deg)</th>
<th>Reflectance (%)</th>
<th>FWHM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0</td>
<td>5</td>
<td>32.2</td>
<td>0.08</td>
</tr>
<tr>
<td>9.0</td>
<td>5</td>
<td>36.0</td>
<td>0.11</td>
</tr>
<tr>
<td>10.0</td>
<td>5</td>
<td>39.9</td>
<td>0.15</td>
</tr>
<tr>
<td>11.0</td>
<td>5</td>
<td>46.3</td>
<td>0.23</td>
</tr>
<tr>
<td>12.0</td>
<td>5</td>
<td>49.1</td>
<td>0.33</td>
</tr>
</tbody>
</table>

Measured @PTB Berlin
Multilayers for 17 ... 20 nm

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>AOI</th>
<th>Reflectance</th>
<th>FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.24 nm</td>
<td>5 deg</td>
<td>50.0 %</td>
<td>0.33 nm</td>
</tr>
<tr>
<td>17.49 nm</td>
<td>5 deg</td>
<td>50.7 %</td>
<td>0.60 nm</td>
</tr>
<tr>
<td>17.91 nm</td>
<td>5 deg</td>
<td>51.9 %</td>
<td>0.61 nm</td>
</tr>
<tr>
<td>19.27 nm</td>
<td>5 deg</td>
<td>45.3 %</td>
<td>0.47 nm</td>
</tr>
</tbody>
</table>
Narrowband Multilayers for 30 ... 38 nm

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>AOI</th>
<th>Reflectance</th>
<th>FWHM</th>
<th>ML Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>30.0 nm</td>
<td>5 deg</td>
<td>36.1 %</td>
<td>2.17 nm</td>
<td></td>
</tr>
<tr>
<td>30.0 nm</td>
<td>15 deg</td>
<td>11.5 %</td>
<td>0.60 nm</td>
<td>narrow band</td>
</tr>
<tr>
<td>37.9 nm</td>
<td>15 deg</td>
<td>36.7 %</td>
<td>3.28 nm</td>
<td></td>
</tr>
<tr>
<td>38.0 nm</td>
<td>15 deg</td>
<td>7.4 %</td>
<td>0.86 nm</td>
<td>narrow band</td>
</tr>
</tbody>
</table>

Measured @PTB Berlin
Multilayers for 42 ... 52 nm

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>AOI</th>
<th>Reflectance</th>
<th>FWHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>41.5 nm</td>
<td>1.5 deg</td>
<td>35.6 %</td>
<td>3.86 nm</td>
</tr>
<tr>
<td>52.4 nm</td>
<td>1.5 deg</td>
<td>31.5 %</td>
<td>4.25 nm</td>
</tr>
</tbody>
</table>

Measured @PTB Berlin
Mirrors for 40 ... 120 nm

\[ R > 30.0 \% \]
\[ \lambda = 60 \ldots 120 \text{ nm} \]

\[ \text{AOI} = 1.76 \text{ deg.} \]

Measured @PTB Berlin
Mirrors for 110 ... 140 nm

- R > 80.0 %
- $\lambda = 120 ... 140$ nm
- AOI = 1.76 deg.

Measured @PTB Berlin
Gold coated synchrotron optics
EUV optics – made by optiX fab
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Water window microscopy
Laboratory Transmission X-ray Microscope (LTXM)
### Slab Laser System

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Energy</td>
<td>Up to 100 mJ</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>0.4 .. 1 ns</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>1.3 kHz</td>
</tr>
<tr>
<td>Average Power</td>
<td>&gt; 130 W</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1064 nm</td>
</tr>
<tr>
<td>$M^2$</td>
<td>$\approx 3$ (horiz. axis)</td>
</tr>
</tbody>
</table>
Liquid nitrogen jet target system

Laser beam focus

Horizontal: 10.5 ± 0.5 μm
Vertical: 11.4 ± 0.5 μm
Laboratory Transmission X-ray Microscope (LTXM)

Multilayer condenser mirror

- Beam stop
- Filter
- Objective zone plate
- Sample
- Back illuminated CCD
  2048x2048 pixel

**Multilayer condenser**

- Coating: Cr / V
- Wavelength: (2.478 ± 0.01) nm
- Bandwidth: 8 pm
- Mean reflectivity: Up to 0.6%
- Radial aperture: 54 mm
- Throughput: > 2*10^-4 sr

![Multilayer condenser](image)
Current water window multilayer collector: optical performance
Multilayer development for water window collector

Reflectivity in water window region (s-pol @ AOI = 1.5deg)
New multilayer collector mirror: EUV reflectance at different radii

Reflectivity curves from Phi = 0deg to Phi = 180deg @ AOI = 1.5deg
for water window collector N4604 / 00AA59

Reflectivity vs. Wavelength, nm

Target Wavelength = 2.478 nm
Collector mirror: Peak reflectance at different positions

Reflectivity @ ctw100 of water window collector N4604 / 00AA59

- Reflectivity, %
  - 4.450
  - 4.500
  - 4.550
  - 4.600
  - 4.650
  - 4.700
  - 4.750
  - 4.800
  - 4.850
  - 4.900
  - 4.950
- Radius, mm
  - -25
  - -20
  - -15
  - -10
  - -5
  - 0
  - 5
  - 10
  - 15
  - 20
  - 25

Lines:
- 0deg --> 180deg (Blue)
- 45deg --> 225deg (Green)
- 90deg --> 270deg (Purple)
- 135deg --> 315deg (Teal)
Collector mirror: Center wavelength at different positions

ctw100 wavelength water window collector N4604 (Sub.ID: 00AA59)

Wavelength, nm

Radius, mm

0deg -> 180deg, 45deg -> 225deg, 90deg -> 270deg, 135deg -> 315deg, target = 2.478 nm
Collector mirror: Reflectance mapping at $\lambda = 2.478$ nm

- Reflectance mapping at $\lambda = 2.478$ nm
- $R = 3.66\%$
- $\lambda = 2.478$ nm
- $\text{FWHM} = 0.005$ nm
- $\text{AOI} = 1.5$ deg.
- Measured @PTB Berlin
Laboratory Transmission X-ray Microscope: Resolution

Δx = 35±3 nm

C. Seim, H. Legall, H. Stiel et al SPIE (2013) 8678, 867808
Cryo fixated yeast cells (*Saccharomyces cerevisiae*) with 250 nm Gold nanoparticles
Laboratory Transmission X-ray Microscope: Biological Imaging

penetration of submicron- and nanoparticles into human skin

structural analysis of human bone by means of soft X-ray microscopy
Laboratory Transmission X-ray Microscope: Biological Imaging

X-ray microscopy characterization of ball clay

Institute for X-Optics

structural analysis of (high pressure treated) bacterial endospores

Horticultural Engineering
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Summary

- Fabrication of customized EUV and VUV multilayer optics from 2 nm to 200 nm
- Development of new and high-reflective multilayer for 2.478 nm
- Multilayer reflectance: $R = 18.2\% \ @ \ 2.422 \ nm \ (V \ absorption \ edge)$
- Multilayer reflectance: $R = 5.6\% \ @ \ 2.478 \ nm \ (N_2 \ emission)$
- Collector reflectance: $R = 3.66\% \ @ \ 2.478 \ nm$
- Factor of 10 improvement!
Acknowledgements

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- **AXILON**: Urs Wiesemann, Wolfgang Diete
- **KTH**: Hans Hertz
Thank you.
optiX fab.

www.optixfab.com