Precision Imaging Multilayer Optics
for Soft X-Ray and Extreme Ultraviolet Ranges

Nikolay I. Chkhalo, Nikolay N. Salashchenko

Institute for Physics of Microstructures RAS, GSP-105 Nizhny Novgorod, Russia

Nano and Giga Challenges in Electronics, Photonics and Renewable Energy
Moscow - Zelenograd, Russia, September 12-16, 2011
OUTLINE

1. What is the optics and most serious PROBLEMS when CHARACTERIZING and MANUFACTURING the optics
2. Latest DEVELOPMENTS in the field of interest are conducting in IPM RAS
3. Applications the optics in science and technology
4. Conclusion
Motivation I. Using short wavelength for achieving nanometer scale space resolution

Space resolution of a lens

\[ \delta x = 0.61 \cdot \frac{\lambda}{NA} \approx \frac{\lambda}{2} \]

where \( NA \) is a numerical aperture, \( \lambda \) is a wavelength, \( \alpha \) – half of an exit aperture angle and \( n \) is a refraction index.

\[ \lambda = 193 \text{ nm} \quad \delta x \approx 100 \text{ nm} \]

In the XEUV wavelength range \( \lambda = 2 - 20 \text{ nm} \quad \delta x << 100 \text{ nm} \)

\( \lambda = 3 \text{ nm} \quad NA = 0.3 \quad \delta x \approx 6 \text{ nm} \)
“A designer knows he has achieved perfection not when there is nothing left to add, but when there is nothing left to take away.” - Antoine de Saint-Exupery

Lithography at 13.5 nm (6.7 nm)

Double patterning

Double exposing

Immersion

Size Reduction Lithography

Tens of superfluous production operation on a chip are removed!
### PROBLEMS!

**Index of Refraction** $n \approx 1$ **and attenuation length** $l \sim 0.01-5 \, \mu m$

**Imaging optics for spectral range of 2-60 nm**

<table>
<thead>
<tr>
<th>#</th>
<th>Kind of optics</th>
<th>NA</th>
<th>Focus length</th>
<th>Operating spectral range</th>
<th>Usability for soft X-rays</th>
<th>Nanometer scale resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mirror and Capillary optics</td>
<td>low</td>
<td>wide range</td>
<td>wide range</td>
<td>yes</td>
<td>only in hard X-ray region</td>
</tr>
<tr>
<td>2</td>
<td>Refractive lenses</td>
<td>low</td>
<td>wide range</td>
<td>$\lambda &lt; 0.5 , \text{nm}$</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>3</td>
<td>Fresnel zone plates</td>
<td>moder</td>
<td>~100 $\mu$</td>
<td>$\lambda &lt; 3 , \text{nm}$</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>4</td>
<td>Multilayer optics</td>
<td>high</td>
<td>wide range</td>
<td>wide range</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>
Multilayer interference structures for spectral range of 2-60 nm

\[ 2d \sin \vartheta = \lambda \quad \Rightarrow \quad d \approx \frac{\lambda}{2} = 1 \div 30 \text{ nm} \]

\[ N = 20-1000 \quad \Rightarrow \quad N = 200-500 \]

\[ \delta d / d < 1 / N \quad \Rightarrow \quad \delta d / d < 0.2\% \]

**Multilayer Interference Structure**

**Requirements to the deposition process are FANTASTIC**

Typical multilayer mirrors produced in IPM RAS. More than 20 pairs of different materials is deposited on flat or curved substrates with diameters from a few up to 300 mm.
The present level of multilayer normal-incidence optics

\[ r \approx r_0 \cdot \exp(-2\pi^2 \sigma^2/d^2) \]

\( \sigma \) should be at a level of 0.1-0.2 nm, which includes roughness and mixing of the layer materials.

So the problem of increasing of the reflection coefficients and moving towards the shorter wavelengths is a problem of INTERFACES!!!!
Requirements to the surface shape and roughness of the mirrors

**The Maresshal criterion on limiting aberration**

\[ RMS_{obj} \leq \lambda / 14 \]

**Shape accuracy in N-mirror systems**

\[ RMS_1 \leq \lambda / (14\sqrt{N}) \]

For \( \lambda = 3 \) nm and \( N = 2 \) \( RMS_{obj} \approx 0.2 \) nm and \( RMS_1 \approx 0.14 \) nm
Problems with traditional approaches to characterize the surface properties

Commercially available interferometers warrant measurement accuracy of surface shape at a level of $RMS_1 \approx 20\text{-}30$ nm

1. Limiting range $v = 2 \times 10^{-2} - 10^2 \text{ } \mu^{-1}$
2. Only flat surfaces

PSD$_{1D}$ functions of SiO$_2$ substrate measured in IPM RAS (1) and Rigaku (2-8) by different methods: 1 – XRDS and AFM, 2 – AFM, 3 – 8 – Zygo interference microscope with magnification 1.25x, 4 – 2.5x, 5 – 5x, 6 – 10x, 7 – 20x and 8 – 40x.
Key technologies required for manufacturing and characterization of the optics

- **Super polishing** of substrates and **metrology** of surface roughness in lateral scales of **1 nm – 1 mm** with sensitivity (quality) \( r.m.s. \approx 0.1 \text{ nm} \)

- **Interferometry** for measurement of wave front aberrations of lens and optical elements with **precision** \( R.M.S. \approx 0.1 \text{ nm} \)

- **Physical methods of correction (finishing)** of optical surfaces with **precision** \( R.M.S. \approx 0.2-0.4 \text{ nm} \)

- **Deposition and precision reflectometry** of multilayer mirrors on substrates with curved surface shape and with a diameter up to a few hundreds of mm

- **Deformation-free mounting** of the precision optical elements into metallic frames
Superpolishing and roughness. The best measured results on effective roughness $\sigma_{\text{eff}}$ in spectral range of $\Delta \nu=0.02-64 \, \mu^{-1}$ of super polished substrates from different manufacturers

<table>
<thead>
<tr>
<th>Material</th>
<th>$\sigma_{\text{eff}}$, nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si (General Optics)</td>
<td>0.43</td>
</tr>
<tr>
<td>Si wafer from South-East Asia</td>
<td>0.22</td>
</tr>
<tr>
<td>Si wafer from South-East Asia</td>
<td>0.62</td>
</tr>
<tr>
<td>Quartz (General Optics)</td>
<td>0.37</td>
</tr>
<tr>
<td>Quartz (General Optics)</td>
<td>0.33</td>
</tr>
<tr>
<td>Quartz (Komposit, Moscow)</td>
<td>0.38</td>
</tr>
<tr>
<td>Cr/Sc MLS on Si (IPM RAS, N.Novgorod)</td>
<td>0.36</td>
</tr>
<tr>
<td>Zerodur (Edmund Industrial Optics)</td>
<td>0.53</td>
</tr>
<tr>
<td>Sapphire (IC RAS, Moscow)</td>
<td>0.20</td>
</tr>
</tbody>
</table>
Characterization aberrations and surface shape of the optics. Interferometer with diffraction reference wave


Experimental setup for studying the wave front deformations of the sources of spherical wave. ($\lambda=530$ нм)

<table>
<thead>
<tr>
<th></th>
<th>RMS, nm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NA</strong></td>
<td>0.1</td>
</tr>
<tr>
<td><strong>ALS, Berkeley</strong></td>
<td>0.08</td>
</tr>
<tr>
<td><strong>IPM RAS</strong></td>
<td>0.02</td>
</tr>
</tbody>
</table>
Correcting procedure

1. Ion gun
2. Mask
3. Processed sample
4. Surface map before correcting
5. Surface map after correcting
6. PDI Interferometer
7. Ion-beam etching facility
Best characteristics of optics manufactured in IPM RAS. Projective objective (NA=0.3) for EUV lithographer.

Concave aspheric mirror

As-prepared surface

Convex aspheric mirror

As-prepared surface

After 27th correcting

PV= 89.6 nm
RMS=17.8 nm

PV= 7.7 nm
RMS=0.9 nm
Reference spherical mirror with $NA=0.25$ for characterization of objectives

As-prepared ZYGO reference:
$P-V = 42.6 \text{ nm}$, $RMS = 7.3 \text{ nm}$

After 12-th correcting:
$P-V = 6.7 \text{ nm}$, $RMS = 0.6 \text{ nm}$
Two Alpha Demo Tools are at research centers

**IMEC (Leuven, Belgium)**
- \( \lambda \) 13.5 nm
- NA 0.25
- Field 26 x 33 mm\(^2\)
- Magnification 4x reduction
- Sigma 0.5
- Chief ray angle at mask is 6 degrees

**CNSE (Albany, NY, USA)**
- Single stage, 300mm wafer, linked to track
- ATHENA alignment sensor
- Single reticle load (no library)
- X REMA only; UNICOM
- Uses TWINSAN technology (e.g., focus)
- Reflective optics
- Sn DPP source
Main Contributions of IPM RAS into the ASML EUV Lithography Developments

- **Multilayer optics and apparatus** for characterization plasma discharge EUV radiation sources and optics contamination
- **Free-standing multilayer filters** for XEUV spectroscopy and Spectral Purity Filters cutting long-wavelength radiation with high withstandability to heat loads in α- and β- machine

In-band reflectometer for measurement of reflectivity losses due to contamination and filter transparency

In-band contour-adapted detector: Looking at the EUV source through a “spectral window of multi-mirror EUVL optics”

**SPF** for α- and β- tools

- $T_{13.5} > 70\%$
- $T_{\text{oper}} > 800\, ^\circ\text{C}$
A stand of EUV-lithographer with a designed resolution of 30 nm (IPM RAS)

- Designed resolution 27 nm
- Field of view on a mask 3×3 mm²
- Demagnification 5×

Objectives
- Demonstration that in Russia there exist unique technologies for developing EUV nanolithography
- A stand for development and optimization photoresists for 13.5 nm
**Motivation II. Using a resonance character of interaction of the XEUV radiation with a matter in a combination with nanometer-scale resolution**

An advantage in using of nanometer-scale resolution optics is forced by a resonance character of interaction of the XEUV radiation with a matter. Due to low scattering, low absorption before and strong absorption below absorption edges, we can study thick, >10 µ, biological (organic) samples with a high absorption contrast of proteins (carbon).

* Presence of strong absorption jumps decrease the required illumination dose by a few orders of magnitude. It means that not hard X-rays, not electrons, only soft X-rays allow studying even living biological cells, or observing nanometer-sized organics in a thick matrix.
Viewing spin structures with soft X-ray microscopy

Images recorded at 15nm spatial resolution of the domain evolution in \((\text{Co}_{0.83}\text{Cr}_{0.17})_{87}\text{Pt}_{13}\) alloy film as function of applied magnetic

X-ray microscopy of the domain configuration for the ON/OFF switch settings.

Extraterrestrial XEUV astronomy. The TESIS project (P.N. Lebedev PhIAS)

An aspherical profile

Optical scheme of the telescope

Photographs of the mirrors for the SEC

Photo of the Sun at $\lambda=30.4$ nm, taken with a satellite Coronas-Photon (2009). Resolution 1.8”

For developing Project ARKA the resolution 0.18”
1. **Conclusion**

1. Diffraction quality XEUV optics opens up new possibilities in nano-lithography and microscopy, in basic physics of nonlinear mediums and nano-electro-magnetism.

2. State-of-the-art technologies of growing multilayer mirrors and substrate manufacturing allow solution a number of the mentioned above tasks.

3. The main problems slowing down wide using of the optics are limiting capabilities of the point diffraction interferometry for testing high-NA aspherical optics and relatively poor surface roughness of substrates and interfaces in short-$d$ MLS.

4. World level laboratory technologies and instrumentation for manufacturing and characterization of diffraction quality imaging optics for XEUV range are developed in IPM RAS.
MANY THANKS
for YOUR ATTENTION!!!