EUV and Soft X-Ray Optics

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The short wavelength region of the electromagnetic spectrum

\[ n = 1 - \delta + i\beta \quad \delta, \beta << 1 \]

\[ \hbar \omega \cdot \lambda = hc = 1239.842 \text{ eV nm} \]

- See smaller features
- Write smaller patterns
- Elemental and chemical sensitivity
Available x-ray optical techniques

- Reflection (glancing incidence or multilayer coatings)

- Diffraction (zone plates, gratings, pinholes)

- Refraction (only for hard x-rays, > 20 keV)

Basic ionization and emission processes in isolated atoms

(a) Electron collision induced ionization
(b) Photoionization
(c) Fluorescent emission of characteristic radiation
(d) Non-radiative Auger process
Energy levels, absorption edges, and characteristic line emissions for a multi-electron atom

Energy levels, quantum numbers, and allowed transitions for the copper atom
Refractive index from the IR to x-ray spectral region

\[ n(\omega) = 1 - \delta + i\beta \]  
(3.12)

\[ \delta = \frac{n_0 \delta \lambda^2}{2\pi f_1^0(\omega)} \]  
(3.13a)

\[ \beta = \frac{n_0 \delta \lambda^2}{2\pi f_2^0(\omega)} \]  
(3.13b)

- \( \lambda^2 \) behavior
- \( \delta \) & \( \beta \) \(<\) 1
- \( \delta \)-crossover

Refractive index at nanometer wavelengths

Refractive Index

\[ n = 1 - \delta + i\beta = 1 - \frac{n_0 \epsilon \lambda^2}{2\pi} (f_{1}^0 - if_{2}^0) \]

Atomic scattering factors

### Si (\( Z = 14 \))

- Refraction
- Absorption
Refractive index in the soft x-ray and EUV spectral region

\[ n(\omega) = 1 - \frac{e^2 n_a}{2 \epsilon_0 m} \sum_s \frac{g_s}{(\omega^2 - \omega_s^2) + i\gamma \omega} \]  (3.8)

Noting that \( r_s = \frac{e^2}{4\pi \epsilon_0 mc^2} \)

and that for forward scattering

\[ f^0(\omega) = \sum_s \frac{g_s \omega^2}{\omega^2 - \omega_s^2 + i\gamma \omega} \]

where this has complex components

\[ f^0(\omega) = f_1^0(\omega) - if_2^0(\omega) \]

The refractive index can then be written as

\[ n(\omega) = 1 - \frac{n_a r_s \lambda^2}{2\pi} [f_1^0(\omega) - if_2^0(\omega)] \]  (3.9)

which we write in the simplified form

\[ n(\omega) = 1 - \delta + i\beta \]  (3.12)

Photoionization and electron binding energies

<table>
<thead>
<tr>
<th>Table 8.1: Electron binding energies in electron volts for the elements in their natural forms.</th>
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<td>Element</td>
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Cheiron School September 2011
Available x-ray optical techniques

- Reflection (glancing incidence or multilayer coatings)

\[ n = \frac{1}{\sin \theta} = \frac{n_f}{n_i} \] (requires \( \theta(0) \ll 1 \))

- Diffraction (zone plates, gratings, pinholes)

- Refraction (only for hard x-rays, > 20 keV)

Diffractive and reflective optics for EUV, soft x-rays and hard x-rays

a) Fresnel zone plate

\[ f = \frac{\lambda^2}{\pi r^2} \]

b) Schwarzschild objective

\[ n_f \times \frac{2\pi r^2}{\lambda} \]

c) Kirkpatrick-Baez mirror pair

Focal spot

\[ M_2 \]

Aperture

Scanning stage

d) Multilayer Laue lens
Diffractive optics for soft x-rays and EUV

Zone Plates

Gratings

Pinholes

Diffraction from a transmission grating

$$\sin \theta_m = \frac{m \lambda}{d}; \quad m = 0, \pm 1, \pm 2, \pm 3, \ldots$$ (9.2)

$$\eta_m = \begin{cases} 
\frac{1}{4} & m = 0 \\
\frac{1}{m^2 \pi^2} & m \text{ odd} \\
0 & m \text{ even}
\end{cases}$$ (9.24)

(50% absorbed)
A Fresnel zone plate lens

\[ f^2 + r_n^2 = \left( f + \frac{n\lambda}{2} \right)^2 \]  \hspace{1cm} (9.8)

\[ r_n^2 = n\lambda f + \frac{n^2\lambda^2}{4} \]  \hspace{1cm} (9.9)

\[ r_n \simeq \sqrt{n\lambda f} \]  \hspace{1cm} (9.10)

A Fresnel zone plate lens used as a diffractive lens for point to point imaging

\[ q_n + p_n = q + p + \frac{n\lambda}{2} \]

\[ q_n = \left( q^2 + r_n^2 \right)^{1/2} \simeq q + \frac{r_n^2}{2q} \]

\[ p_n = \left( p^2 + r_n^2 \right)^{1/2} \simeq p + \frac{r_n^2}{2p} \]

\[ \frac{f^2 + r_n^2}{2q} + \frac{f^2 + r_n^2}{2p} \simeq \frac{f^2}{p} + \frac{f^2}{q} + \frac{n\lambda}{2} \]

\[ \frac{1}{q} + \frac{1}{p} \simeq \frac{1}{f} \]  \hspace{1cm} (9.17)

\[ M = \frac{p}{q} \]  \hspace{1cm} (9.18)
Depth of focus and spectral bandwidth

\[ \Delta z = \frac{1}{2 (NA)^2} \frac{\lambda}{2} \]  
(9.50)

\[ \Delta z = \pm 2 f^2 \frac{\lambda}{2} = \pm 2 (\Delta r)^2 / \lambda \]  
(9.51)

\[ \frac{\Delta \lambda}{\lambda} \leq \frac{1}{N} \]  
(9.52)

A Fresnel zone plate lens for soft x-ray microscopy

Courtesy of E. Anderson, LBNL
Zone plates for ALS STXM beamlines – “3D Engineered Nanostructures”

\[ \Delta r = 35 \text{ nm}, \, \Delta t = 180 \text{ nm} \, \text{Au}, \, N = 1700 \]

\[ D = 240 \, \mu\text{m}, \, 3 \times 95 \, \mu\text{m}^2 \text{ central stop} \]

The Nanowriter: high resolution electron beam writing with high placement accuracy

Courtesy of E. Anderson (LBNL)
Zones plates for soft x-ray image formation

\[ r^2 = \pi f + \frac{\pi \lambda^2}{4} \]  
(9.9)

\[ D = 4N\Delta\lambda \]  
(9.13)

\[ f = \frac{4N\Delta\lambda^2}{\lambda} \]  
(9.14)

\[ NA = \frac{\lambda}{2\Delta\lambda} \]  
(9.15)

\[ \text{Rcs.} = k_1 \frac{\lambda}{NA} = 2k_1\Delta\lambda \]  

\[ \text{DOF} = \pm \frac{1}{2} \left( \frac{\lambda}{NA} \right)^2 \]  
(9.50)

\[ \frac{\Delta\lambda}{\lambda} \leq \frac{1}{N} \]  
(9.52)

\[ \lambda = 2.5 \text{ nm}, \quad \Delta\lambda = 25 \text{ nm} \]  
\[ N = 618 \]

\[ 63 \mu\text{m} \]

\[ 0.63 \text{ mm} \]

\[ 0.05 \]

\[ \frac{1.22\Delta\lambda}{\lambda} = 30 \text{ nm} \]

\[ 0.8\Delta\lambda = 19 \text{ nm} \]

\[ 1 \mu\text{m} \]

\[ 1/700 \]

New x-ray lenses: Improving contrast and resolution for x-ray microscopy

Diffraction limited x-ray imaging

Diffraction limited imaging is limited by the finite wavelength and acceptance aperture:

\[ \Delta r_{\text{resol.}} = k_1 \frac{\lambda}{\text{NA}} \]

where \( \text{NA} = n \sin \theta \) and the constant \( k_1 \) depends on illumination and specific image modulation criteria. For x-rays

\[ n = 1 - \delta + i\beta \quad \delta, \beta \ll 1 \]

For example, the widely accepted Rayleigh criteria for resolving two adjacent, mutually incoherent, point sources of light, results in a 26% intensity modulation.

Two overlapping Airy patterns

Note: Other definitions are possible, depending on the application and the ability to discern separated objects.
Resolution and illumination

Achievable resolution can be improved by varying illumination:

An object pattern of periodicity \( d \) diffracts light and is just captured by the lens – setting the diffraction limited resolution limit.

Diffraction from an object of smaller periodicity, \( d/2 \), is just captured, and resolved, when illuminated from an angle.

Resolution, illumination, and optical transfer function

Spatial frequency response of the optical system can be optimized by tailoring the angular distribution of illumination.

\[
\sigma = \frac{\text{NA}_{\text{cond}}}{\text{NA}_{\text{obj}}}
\]

(10.3)
Hard x-ray imaging based on glancing incidence reflective optics

- Optics behave differently at these very short wavelengths (nanometers rather than 520 nm green light)
- The refractive index is less than unity, $n = 1 - \delta + i\beta$
- Waves bend away from the normal at an interface
- Absorption is significant in all materials and at all wavelength.
- Because of absorption, refractive lenses do not work, prisms do not, windows need to be extremely thin (100 nm or less).
- Because light is bent away from the surface normal, it possible to have "total external reflection" at glancing incidence – a commonly used technique.
- Kirkpatrick-Baez (KB) mirror pair
Glancing incidence optics

Snell’s Law:
\[ \sin \phi_{\text{refr}} = \frac{\sin \theta}{n} \]

Total external Reflection:
\[ \phi_{\text{refr}} \to \frac{\pi}{2} \text{ as } \theta \to \phi_{\text{critical}} \]
\[ \sin \phi_{\text{critical}} = \frac{\sin \phi}{1 - \delta} \]
\[ \sin(90^\circ - \theta_c) = 1 - \delta \]
\[ \cos \theta_c = 1 - \delta \]
\[ 1 - \frac{\theta_c^2}{2} = 1 - \delta \]
\[ \theta_c = \sqrt{2\delta} \]

For gold at 1 keV
\[ \delta = 2.1 \times 10^{-3} \]
\[ \theta_c = 3.7^\circ \]

Total external reflection with finite \( \beta \)

Glancing incidence reflection as a function of \( \beta \delta \)

- finite \( \beta \delta \) rounds the sharp angular dependence
- cutoff angle and absorption edges can enhance the sharpness
- note the effects of oxide layers and surface contamination

\[ \text{Reflector (a)}: \beta \delta = 0 \]
\[ \text{Reflector (b)}: \beta \delta = 10^{-2} \]
\[ \text{Reflector (c)}: \beta \delta = 10^{-1} \]
\[ \text{Reflector (d)}: \beta \delta = 1 \]
\[ \text{Reflector (e)}: \beta \delta = 3 \]

... for real materials

- Carbon (C)
- Aluminum (Al)
- Aluminum Oxide (Al₂O₃)
- Gold (Au)
Normal incidence reflection at an interface

\[ R_r = \frac{\cos \phi - \sqrt{n^2 - \sin^2 \phi}}{\cos \phi + \sqrt{n^2 - \sin^2 \phi}} \quad (3.49) \]

at \( \phi = 0 \):

\[ R_{r,\perp} = \frac{|1 - n|^2}{|1 + n|^2} = \frac{(1 - n)(1 - n^*)}{(1 + n)(1 + n^*)} \]

For \( n = 1 - \delta + i\beta \)

\[ R_{r,\perp} = \frac{(\delta - i\beta)(\delta + i\beta)}{(2 - \delta + i\beta)(2 - \delta - i\beta)} = \frac{\delta^2 + \beta^2}{(2 - \delta)^2 + \beta^2} \]

Reflectivity for x-ray and EUV radiation at normal incidence (\( \phi = 0 \)):

\[ R_{r,\perp} \simeq \frac{\delta^2 + \beta^2}{4} \quad (3.50) \]

Example: Nickel @ 300 eV (4.13 nm)

\( f_1 = 17.8 \quad f_2 = 7.70 \quad \delta = 0.0124 \quad \beta = 0.00538 \)

\( R_{\perp} = 4.58 \times 10^{-5} \)

Focusing with curved glancing incidence optics

The Kirkpatrick-Baez mirror system

(Courtesy of J. Underwood)

- Two crossed cylinders (or ellipses)
- Astigmatism cancels
- Common use in synchrotron radiation beamlines
- Hard x-ray microprobe
Fluorescent microprobe based in crossed cylinders

Kirkpatrick-Baez (KB) optics

- Crossed cylinders at glancing incidence
- Ellipses better
- Photon in / photon out, low noise background
- Femtogram and part per billion (ppb) sensitivity
- Sub-micron focus (to 0.1 μm recently), but scattering gives several micron “50% encircled energy”
- K-B optics have many applications to synchrotron beamlines, fusion diagnostics, etc.

High resolution x-ray diffraction under high pressure using multilayer coated focusing optics

X-ray microprobe at SPring-8

Front end

Undulator

DCM

TC1Slit

Incident Slit

Mirror manipulator

Ion chamber

Beam monitor

Sample & Scanner

Optical microscope

PIN photodiode

SDD

Sample & Scanner

Courtesy of K. Yamauchi and H. Mimura, Osaka University.

A high quality Mo/Si multilayer mirror

N = 40
d = 6.7

Courtesy of Saša Bajt (LLNL)
Scattering by density variations within a multilayer coating

(T. Nguyen, CXRO/LBNL)

Multilayer mirrors satisfy the Bragg condition

For normal incidence, \( \theta = \pi/2 \), first order \((m = 1)\) reflection

\[ m\lambda = 2d \sin \theta \]

if the two layers are approximately equal

\[ \Delta t = \lambda/4 \]

a quarter-wave plate coating.
Multilayer mirrors satisfy the Bragg condition

\[ m\lambda = 2d \sin \theta \left(1 - \frac{4\delta d^2}{m^2 \lambda^2}\right) \]

- For normal incidence, \( \theta = \pi/2 \), first order (\( m = 1 \)) reflection
  \( \lambda = 2d \)
  \( d = \lambda/2 \)
- If the two layers are approximately equal
  \( \Delta t = \lambda/4 \)
- A quarter-wave plate coating.

High reflectivity, thermally and environmentally robust multilayer coatings for high throughput EUV lithography

- Ru capping layer
- Si
- Mo/C
- Mo/B_{12}/C
- Mo

\( \lambda = 13.4 \text{ nm} \)

- Ru (1.70 nm)
- Si (4.14 nm)
- B_{12}/C (0.25 nm)
- Mo (2.09 nm)
- B_{12}/C (0.40 nm)

\( d = 6.88 \text{ nm} \)
\( \Gamma = 0.54 \)

Reflectivity

- Mo/B_{12}/C/Si
  - 70% at 13.5 nm
  - FWHM = 0.55 nm
  - 50 bilayers

Courtesy of Swiss Bad (LLNL)
Atomic scattering factors for silicon (Z = 14)

<table>
<thead>
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<th>Energy (eV)</th>
<th>$f_1$</th>
<th>$f_2$</th>
<th>$\mu$ (cm$^2$/g)</th>
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Edge Energies: K 1938.9 eV  L$_3$ 497 eV  L$_2$ 99.2 eV  L$_1$ 99.2 eV

(Henke and Gullikson; [www.xro.lbl.gov](http://www.xro.lbl.gov))

Atomic scattering factors for molybdenum (Z = 42)

<table>
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<th>Energy (eV)</th>
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Edge Energies: K 19999.5 eV  L$_3$ 2860.5 eV  L$_2$ 2623.1 eV  L$_1$ 2538.2 eV

(Henke and Gullikson; [www.xro.lbl.gov](http://www.xro.lbl.gov))
CXRO Web Site

www.cxro.lbl.gov/

- Atomic scattering factors
- EUV/x-ray properties of the elements
- Index of refraction for compound materials
- Absorption, attenuation lengths, transmission
- EUV/x-ray reflectivity (mirrors, thin films, multilayers)
- Transmission grating efficiencies
- Multilayer mirror achievements
- Other

Sputtered deposition of a multilayer coating

[Diagram showing sputtered deposition process]
Multilayer coatings – “1D nanostructures”

Eric Gullikson, Farhad Salmassi, Yanwei Liu, Andy Aquila (grad), Franklin Dollar (UG)

World reference standard

Creating uniformity for λ/50 optics

World record in water window

Wide band, narrow band, and chirped mirrors for fsec applications

Recent progress in multilayer mirrors

Near-Normal Incidence Multilayer Mirrors

Peak reflectance (%) vs Wavelength (nm)

H₂O window
Broad bandwidth mirrors needed for as/fs pulses

\[ \Delta \varepsilon (eV) \cdot \Delta \tau (fs) \geq 1.8 \, fs \cdot eV \text{ (FWHM)} \]

- Multilayer mirrors depend on constructive interference from individual interfaces
- Higher reflectivity needs more layers
- Bandwidth gets narrower with more layers

Attosecond pulse
- \( \rightarrow \) Broad bandwidth
- \( \rightarrow \) Limited number of layers

N<10 layers required for 200 as pulse (@13nm)

Aperiodic multilayers for asec application

Optimizing multilayers for specific applications requires the use of simulation of a multilayer stack with variations in the thickness of each material in the multilayer.

Successful design of aperiodic multilayers requires:
1. EM wave in multilayer structure
2. Optimization Algorithm
3. Sample preparation
4. Verification

The Cassegrain Telescope with multilayer coatings for EUV imaging of the solar corona

Multilayer Laue Lens for focusing hard x-rays
Photon energy, wavelength, power

\[ \hbar \omega \cdot \lambda = hc = 1239.842 \text{ eV nm} \] \hspace{1cm} (1.1)

1 joule \(\Rightarrow\) \(5.034 \times 10^{15} \lambda[\text{nm}]\) photons \hspace{1cm} (1.2a)

1 watt \(\Rightarrow\) \(5.034 \times 10^{15} \lambda[\text{nm}] \frac{\text{photons}}{\text{s}}\) \hspace{1cm} (1.2b)

Lectures online at www.youtube.com

Amazon.com

UC Berkeley
www.coe.berkeley.edu/AST/sxreuv
www.coe.berkeley.edu/AST/srms
www.coe.berkeley.edu/AST/sxr2009