

EUV, Soft and Hard X-Ray Optics and Beamlines

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The short wavelength region of the electromagnetic spectrum





Available x-ray optical techniques

 $n = 1 - \delta + i\beta$

(requires $\beta/\delta \ll 1$)



• Reflection (glancing incidence or multilayer coatings)



A. Snigerev et al., *Nature* <u>384</u>, 49 (7Nov.1996) B. Lengeler et al., *J. Appl. Phys.* <u>84</u>, 5855 (1Dec.1998)

AvailOpticTechSXREUV.ai

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Basic ionization and emission processes in isolated atoms



(c) Fluorescent emission of characteristic radiation





Energy levels, absorption edges, and characteristic line emissions for a multi-electron atom





Energy levels, quantum numbers, and allowed transitions for the copper atom





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Refractive index from the IR to x-ray spectral region





Refractive index at nanometer wavelengths



Refractive Index

$$n = 1 - \delta + i\beta = 1 - \frac{n_a r_e \lambda^2}{2\pi} (f_1^0 - i f_2^0)$$

Atomic scattering factors



ScattrngRefracIndex_June2009.ai

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



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

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Noting that

$$r_e = \frac{e^2}{4\pi\epsilon_0 mc^2}$$

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

$$n(\omega) = 1 - \frac{n_a r_e \lambda^2}{2\pi} \left[f_1^0(\omega) - i f_2^0(\omega) \right]$$
(3.9)

which we write in the simplified form

 $n(\omega) = 1 - \delta + i\beta \tag{3.12}$

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Photoionization and electron binding energies



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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 form 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







GlancngIncidncOptics.ai

Total external reflection with finite β



Glancing incidence reflection as a function of β/δ



- finite β/δ rounds the sharp angular dependence
- cutoff angle and absorption edges can enhance the sharpness
- note the effects of oxide layers and surface contamination

... for real materials



CXRO Web Site





Facilities Publications Research X-Ray Tools Visitors Personnel Comments? Server Stats

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

Focusing with curved glancing incidence optics





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

Ch03_FocusCurv_Sept2010.ai



beamlines, fusion diagnostics, etc.

FluoresMicroprobe.ai

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





X-ray microprobe at SPring-8





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Normal incidence reflection at an interface



$$R_{s} = \frac{\left|\cos\phi - \sqrt{n^{2} - \sin^{2}\phi}\right|^{2}}{\left|\cos\phi + \sqrt{n^{2} - \sin^{2}\phi}\right|^{2}}$$
(3.49)

at $\phi = 0$:

$$R_{s,\perp} = \frac{|1-n|^2}{|1+n|^2} = \frac{(1-n)(1-n^*)}{(1+n)(1+n^*)}$$

For $n = 1 - \delta + i\beta$

$$R_{s,\perp} = \frac{(\delta - i\beta)(\delta + i\beta)}{(2 - \delta + i\beta)(2 - \delta - i\beta)} = \frac{\delta^2 + \beta^2}{(2 - \delta)^2 + \beta^2}$$

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

$$R_{s,\perp} \simeq \frac{\delta^2 + \beta^2}{4} \tag{3.50}$$

$$\begin{array}{c} \underline{\text{Example:}} & \text{Nickel } @ \ 300 \ \text{eV} \ (4.13 \ \text{nm}) \\ & f_1^\circ = 17.8 & f_2^\circ = 7.70 \\ & \delta = 0.0124 & \beta = 0.00538 \end{array} \right\} \ \text{R}_\perp = 4.58 \times 10^{-5} \end{array}$$

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Diffractive optics for soft x-rays and EUV





Diffraction from a transmission grating





A Fresnel zone plate lens





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



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Depth of focus and spectral bandwidth





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A Fresnel zone plate lens for soft x-ray microscopy





Courtesy of E. Anderson, LBNL









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BERKELEY LAB



Courtesy of E. Anderson (LBNL)

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





C. Chang, A. Sakdinawat, P.J. Fischer, E.H. Anderson, D.T. Attwood, Opt. Lett. 2006; Sakdinawat and Liu, Opt. Lett. 2007; Sakdinawat and Liu, Opt. Express 2008

Diffraction limited x-ray imaging



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



Resolution and illumination

from an angle.



Achievable resolution can be improved by varying illumination:



Lens

Resolution, illumination, and optical transfer function





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



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ETTERS

Nature

Soft X-ray microscopy at a spatial resolution better than 15 nm

Weilun Chao^{1,2}, Bruce D. Harteneck¹, J. Alexander Liddle¹, Erik H. Anderson¹ & David T. Attwood^{1,2}

Analytical tools that have spatial resolution at the nanometre scale are indispensable for the life and physical sciences. It is desirable that these tools also permit elemental and chemical identification on a scale of 10 nm or less, with large penetration depths. A variety of techniques1-7 in X-ray imaging are currently being developed that may provide these combined capabilities. Here we report the achievement of sub-15-nm spatial resolution with a soft X-ray microscope-and a clear path to below 10 nm-using an overlay technique for zone plate fabrication. The microscope covers a spectral range from a photon energy of 250 eV (~5 nm wavelength) to 1.8 keV (~0.7 nm), so that primary K and L atomic resonances of elements such as C, N, O, Al, Ti, Fe, Co and Ni can be probed. This X-ray microscopy technique is therefore suitable for a wide range of studies: biological imaging in the water window^{8,9}; studies of wet environmental samples10,11; studies of magnetic nanostructures with both elemental and spin-orbit sensitivity¹²⁻¹⁴; studies that require viewing through thin windows, coatings or substrates (such as buried electronic devices in a silicon chip¹⁵); and three-dimensional imaging of cryogenically fixed biological cells9,16.

The microscope XM-1 at the Advanced Light Source (ALS) in Berkeley¹⁷ is schematically shown in Fig. 1. The microscope type is similar to that pioneered by the Göttingen/BESSY group (ref. 18, and references therein). A 'micro' zone plate (MZP) projects a full-field image to an X-ray-sensitive CCD (charge-coupled device), typically in one or a few seconds, often with several hundred images per day. The field of view is typically 10 μ m, corresponding to a magnification of 2,500. The condenser zone plate (CZP), with a central stop, serves two purposes in that it provides partially coherent hollow-cone illumination², and, in combination with a pinhole, serves as the



Figure 1 | A diagram of the soft X-ray microscope XM-1. The microscope uses a micro zone plate to project a full field image onto a CCD camera that is sensitive to soft X-rays. Partially coherent, hollow-cone illumination of the sample is provided by a condenser zone plate. A central stop and a pinhole provide monochromatization.

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monochromator. Monochromatic radiation of $\lambda/\Delta\lambda = 500$ is used. Both zone plates are fabricated in-house, using electron beam lithography¹⁹.

The spatial resolution of a zone plate based microscope is equal to $k_1 \Lambda NA_{MZP}$ where λ is the wavelength, NA_{MZP} is the numerical aperture of the MZP, and k_1 is an illumination dependent constant, which ranges from 0.3 to 0.61. For a zone plate lens used at high magnification, $NA_{MZP} = \lambda/2\Delta T_{MZP}$ where Δr_{MZP} is the outermost (smallest) zone width of the MZP^{30}. For the partially coherent illumination: $0.8\Delta_{MZP}$, as calculated using the SPLAT computer program³³ (a two-dimensional scalar diffraction code, which evaluates partially coherent imaging). In previous results with a $\Delta r_{MZP} = 25$ nm zone plate, we reported' an unambiguous spatial resolution of 20 nm. Here we describe the use of an overlay nanofabrication technique that allows us to fabricate zone plates with finer outer zone widths, to $\Delta r_{MZP} = 15$ nm, and to achieve a spatial resolution of below 15 nm, with clear potential for further extension.

This technique overcomes nanofabrication limits due to electron beam broadening in high feature density patterning. Beam broadening results from electron scattering within the recording medium (resist), leading to a loss of image contrast and thus resolvability for $\lambda = 1.52 \text{ nm} (815 \text{ eV})$ $\Delta r = 15 \text{ nm}$ N = 500 $D = 30 \mu \text{m}$ $f = 300 \mu \text{m}$ $\sigma = 0.38$ $0.8 \Delta r = 12 \text{ nm}$



Figure 4 \mid Soft X-ray images of a 15.1 nm half-period test object , as formed with zone plates having outer zone widths of 25 nm and 15 nm.

Cr/Si test pattern (Cr L₃ @ 574 eV) (2000 X 2000, 10⁴ ph/pixel)





- Shorter wavelengths, potentially better spatial resolution and greater depth-of-field.
- Less absorption (β); phase shift (δ) dominates, higher efficiency.
- Thicker structures required (e.g., zones), higher aspect ratios pose nanofabrication challenges.
- Contrast of nanoscale samples minimal; will require good statistics, uniform background, dose mitigation.



New ultra high aspect ratio, high efficiency, hard x-ray zone plates for high spatial resolution at 30-50 keV





Δr = 100 nm $\Delta h = 6.6 \ \mu m$

Courtesy of Anne Sakdinawat and Chieh Chang (SLAC)







Spiral zone plate for producing x-rays with charge 50 orbital angular momentum

NATIONAL ACCELERATOR LABORATORY

> Uniformly redundant array for x-ray parallel holography, alignment, and other applications

Zone plate for x-ray differential interference contrast microscopy

Courtesy of Anne Sakdinawat and Chieh Chang (SLAC)

A high quality Mo/Si multilayer mirror







Courtesy of Saša Bajt (LLNL)

Scattering by density variations within a multilayer coating





(T. Nguyen, CXRO/LBNL)

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Multilayer mirrors satisfy the Bragg condition





Ch04_MltlyrMirBragg1.ai

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



Courtesy of Saša Bajt (LLNL)





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Atomic scattering factors for molybdenum (Z = 42)



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Sputtered deposition of a multilayer coating







Beamlines are used to transport photons to the sample, and take a desired spectral slice



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A typical beamline: monochromator plus focusing optics to deliver radiation to the sample



High spectral resolution (meV beamline)





meVresBL.ai

Courtesy of Zahid Hussein (ALS)



Beamline 7.0 at Berkeley's Advanced Light Source







MAESTRO: A new varied-line-space grating monochromator beam line for angle-resolved-photo-electron-spectroscopy with high spectral and spatial resolution at the Advanced Light Source



Jason Wells, Derek Yegian, Ken Chow, Eli Rotenberg, Aaron Bostwick, Geoff Gaines and Tony Warwick



The latest soft x-ray undulator spectroscopy beam line planned for the ALS serves **MAESTRO** a new high resolution Angle Resolved Photo Emission facility with zone-plate focused nano-ARPES. The beam line design offers spectral resolution 1:30000 from 60eV to 400eV with an extended energy range from 20eV to 1000eV. Challenges include optical figure quality, thermal engineering, source size and stability and vibrations in the monochromator. The optical design is radical in that a VLS grating will provide all of the focusing in the dispersion direction, and the mirrors are plane, except for a sphere to collect and focus horizontally.

Varied line space gratings



Varied-Line-Space Plane Gratings provide focusing and aberration correction along with the dispersion that they generate in the monochromator. They can be used to erect the monochromator focal plane, making the position of the focus at the exit slit (almost) stationary as the grating rotates to select the photon energy. Beyond that, they are now being used to replace the focusing from shaped optics, making beam lines cheaper and easier to align.





MAESTRO: A new varied-line-space grating monochromator beam line at the ALS











Water-cooled optics are essential: correcting slope errors due to a thermal bump







l201 Plane - Slope Errors (μRad)	over full mir	ror substrate	over clear aperture		
ternally cooled Glidcop, 10K W/m ² K)	60eV	20eV	60eV	20eV	
Maximum Tangential Slope Error	28.2	61.3	28.2	61.3	
Average Tangential Slope Error	2.4	4.9	3.0	6.1	
RMS Tangential Slope Error	3.3	7.0	4.4	9.3	
Maximum Sagittal Slope Error	36.4	75.1	36.4	75.1	
Average Sagittal Slope Error	7.3	15.3	13.9	29.2	
RMS Sagittal Slope Error	12.2	25.6	18.0	38.0	







Significant degradation of the spectral resolution occurs due to localized heating of M202. It is almost entirely corrected by adjusting the monochromator focusing parameter from 3.93 to 4.02. The engineering design will allow this mirror to be built with 1mm thick hot-wall and the actual thermal deformation is expected to be less.



Typical parameters for synchrotron radiation



Facility	ALS	New Subaru	APS	SP-8
Electron energy	1.90 GeV	1.00 GeV	7.00 GeV	8.00 GeV
γ	3720	1957	13,700	15,700
Current (mA)	400	100	100	100
Circumference (m)	197	119	1100	1440
RF frequency (MHz)	500	500	352	509
Pulse duration (FWHM) (ps)	35-70	26	100	120
Bending Magnet Radiation:				
Bending magnet field (T)	1.27	1.03	0.599	0.679
Critical photon energy (keV)	3.05	0.685	19.5	28.9
Critical photon wavelength	0.407 nm	1.81 nm	0.636 Å	0.429 Å
Bending magnet sources	24	4	35	23
Undulator Radiation:				
Number of straight sections	12	4	40	48
Undulator period (typical) (cm)	5.00	5.40	3.30	3.20
Number of periods	89	200	72	140
Photon energy $(K = 1, n = 1)$	457 eV	117 eV	9.40 keV	12.7 keV
Photon wavelength ($K = 1, n = 1$)	2.71 nm	10.6 nm	1.32 Å	0.979 Å
Tuning range $(n = 1)$	230-620 eV	43-170 eV	3.5-12 keV	4.7-19 keV
Tuning range $(n = 3)$	690-1800 eV	130-500 eV	10-38 keV	16-51 keV
Central cone half-angle $(K = 1)$	35 µrad	44 µrad	11 µrad	6.6 µrad
Power in central cone $(K = 1, n = 1)$ (W)	2.3	0.15	12	16
Flux in central cone (photons/s)	3.1×10^{16}	7.9×10^{15}	7.9×10^{15}	7.9×10^{15}
$\sigma_{\rm x}, \sigma_{\rm y} (\mu {\rm m})$	260, 16	450, 220	320, 50	380, 6.8
σ'_{x}, σ'_{y} (µrad)	23, 3.9	89, 18	23, 7	16, 1.8
Brightness $(K = 1, n = 1)^a$		č.		
$[(\text{photons/s})/\text{mm}^2 \cdot \text{mrad}^2 \cdot (0.1\%\text{BW})]$	2.3×10^{19}	1.7×10^{17}	5.9×10^{18}	1.8×10^{20}
Total power ($K = 1$, all n , all θ) (W)	83	27	350	2,000
Other undulator periods (cm)	3.65, 8.00, 10.0	7.60	2.70, 5.50, 12.8	2.4, 10.0, 3.7, 12.0
Wiggler Radiation:				
Wiggler period (typical) (cm)	16.0		8.5	12.0
Number of periods	19		28	37
Magnetic field (maximum) (T)	2.1		1.0	1.0
K (maximum)	32		7.9	11
Critical photon energy (keV)	5.1		33	43
Critical photon wavelength	0.24 nm		0.38 Å	0.29 Å
Total power (max. K) (kW)	13		7.4	18

^{*a*}Using Eq. (5.65). See comments following Eq. (5.64) for the case where $\sigma'_{x, y} \simeq \theta_{cen}$.

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Time structure of synchrotron radiation



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The axial electric field within the RF cavity, used to replenish lost (radiated) energy, forms a potential well "bucket" system that forces electrons into axial electron "bunches". This leads to a time structure in the emitted radiation.







Ch01_Eqs1.1_2.ai

2nd Edition in progress: new FEL, HHG, Coherence, and X-ray Imaging chapters





www.coe.AST.berkeley.edu/sxr2009 www.coe.AST.berkeley.edu/srms www.youtube.com