EUV and Soft X-Ray Optics

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Cheiron School
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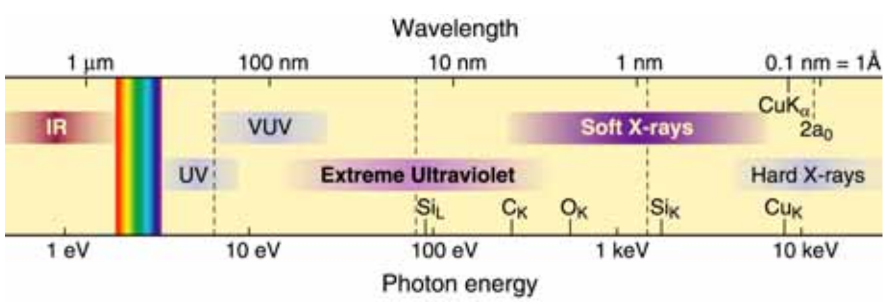
SPring-8

The short wavelength region of the electromagnetic spectrum



- See smaller features
- Write smaller patterns
- Elemental and chemical sensitivity

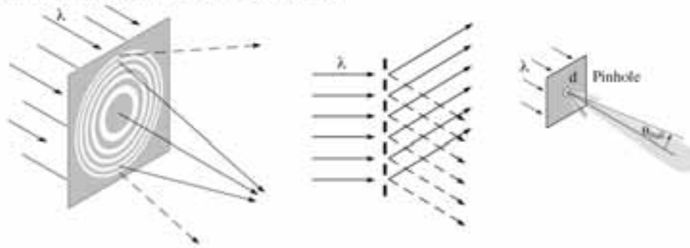
$$\hbar\omega \cdot \lambda = hc = 1239.842 \text{ eV nm}$$

$$n = 1 - \delta + i\beta \qquad \delta, \beta << 1$$

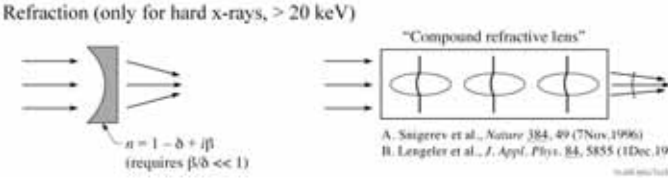
Available x-ray optical techniques

• Reflection (glancing incidence or multilayer coatings)

• Diffraction (zone plates, gratings, pinholes)

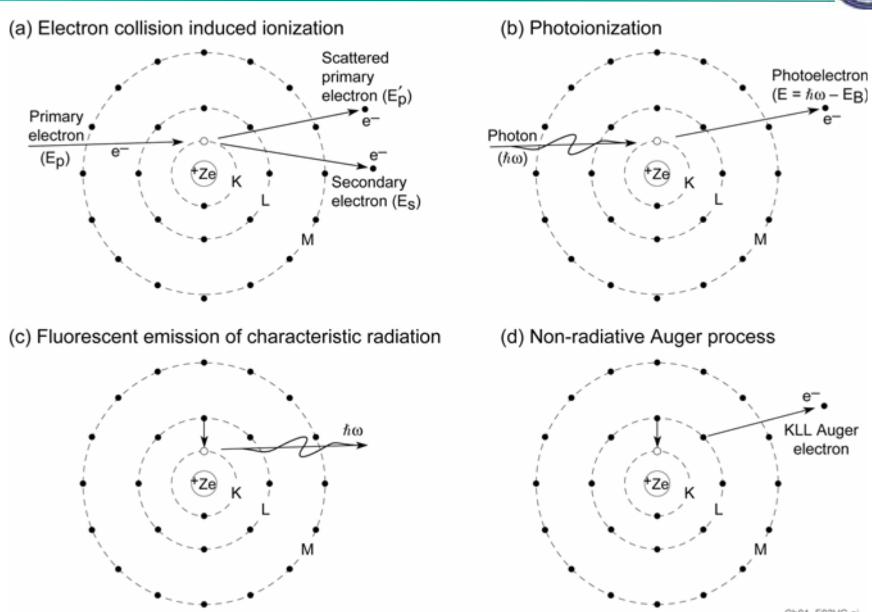


• Refraction (only for hard x-rays, > 20 keV)

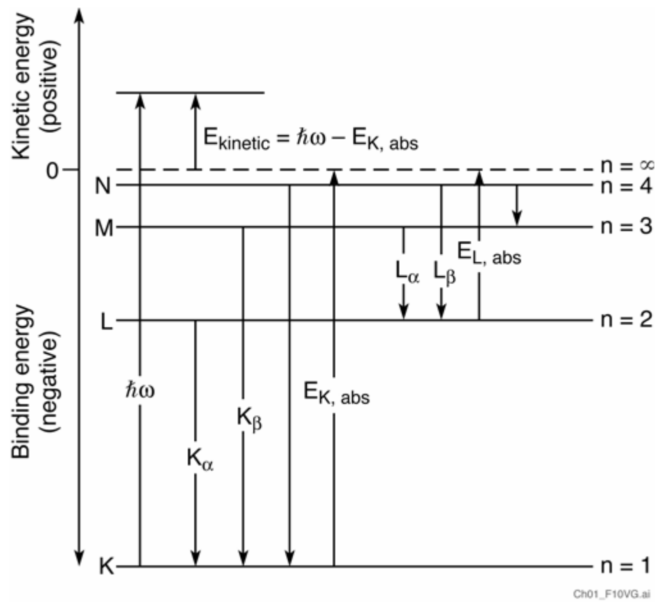


A. Snigerev et al., *Nature* 384, 49 (7Nov.1996)
B. Lengeler et al., *J. Appl. Phys.* 84, 5855 (1Dec.1998)

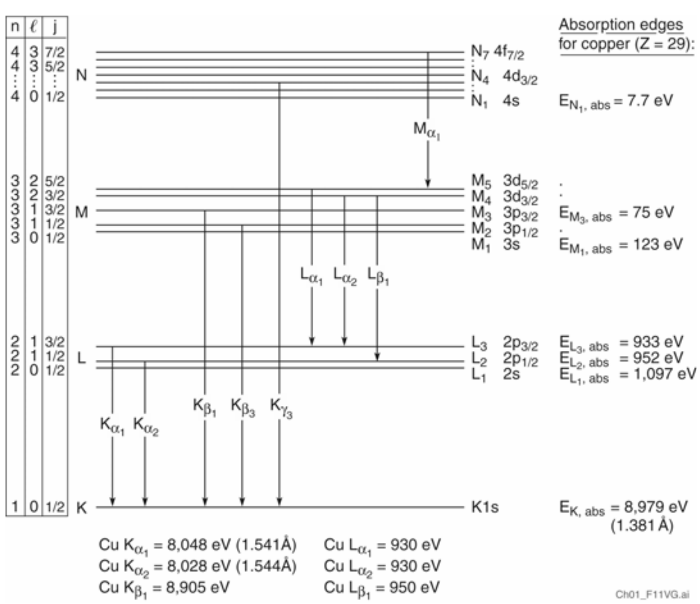
Basic ionization and emission processes in isolated atoms



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



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

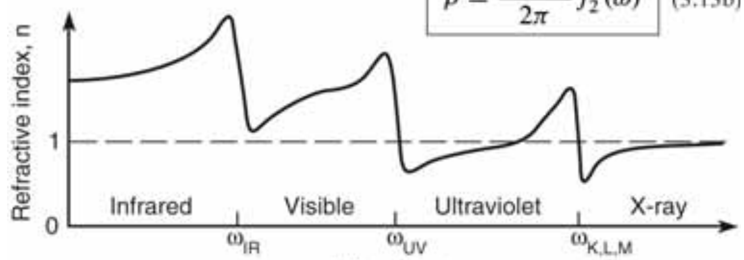


Refractive index from the IR to x-ray spectral region

$$n(\omega) = 1 - \delta + i\beta \quad (3.12)$$

$$\delta = \frac{n_a r_e \lambda^2}{2\pi} f_1^0(\omega) \quad (3.13a)$$

$$\beta = \frac{n_a r_e \lambda^2}{2\pi} f_2^0(\omega) \quad (3.13b)$$



- λ^2 behavior
- δ & $\beta << 1$
- δ-crossover

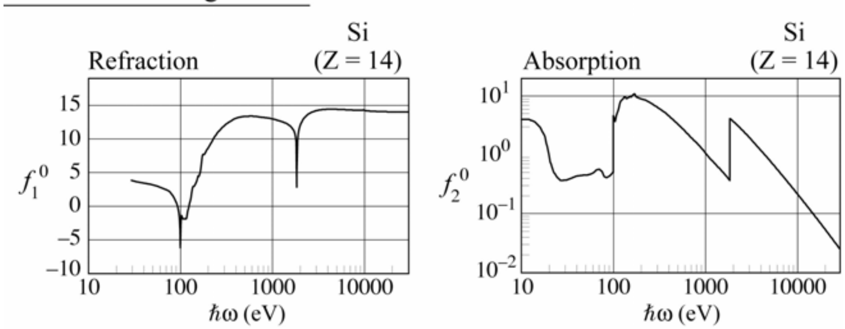
Ch03_RefrcIndxIR-XR.ai

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

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

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

$$f^0(\omega) = f_1^0(\omega) - i f_2^0(\omega)$$

The refractive index can then be written as

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

which we write in the simplified form

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

Ch03_RefracIndex2.ai

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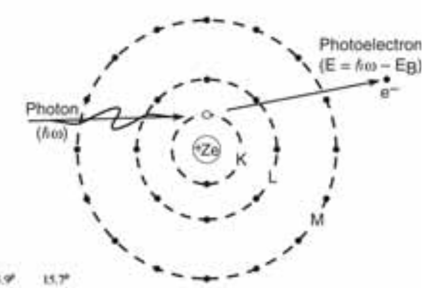
Photoionization and electron binding energies

TABLE B.1. Electron binding energies in electron volts for the elements in their natural forms.[a]

Element	K 1s	L_1 2s	L_2 $2p_{1/2}$	L_3 $2p_{3/2}$	M_1 3s	M_2 $3p_{1/2}$	M_3 $3p_{3/2}$	M_4 $3d_{3/2}$	M_5 $3d_{5/2}$	N_1 4s	N_2 $4p_{1/2}$	N_3 $4p_{3/2}$
1 H	13.6											
2 He	24.6											
3 Li	54.7											
4 Be	111.5											
5 B	188											
6 C	284.2											
7 N	409.9	37.3										
8 O	543.1	41.6										
9 F	696.7											
10 Ne	870.2	48.5	21.7	21.6								
11 Na	1070.8	63.5	30.4	30.5								
12 Mg	1303.0	88.6	49.6	49.2								
13 Al	1559.6	117.8	72.9	72.5								
14 Si	1838.9	149.7	99.8	99.2								
15 P	2145.5	189	136	135								
16 S	2472	230.9	163.6	162.5								
17 Cl	2822.4	270.2	202	200								
18 Ar	3205.9	326.3	250.6	248.4	29.3	15.9	15.7					
19 K	3608.4	378.6	297.3	294.6	34.8	18.3	18.3					
20 Ca	4038.5	438.4	349.7	346.2	44.3	25.4	25.4					
21 Sc	4492.8	498.0	403.6	398.7	51.1	28.3	28.3					
22 Ti	4966.4	560.9	461.2	453.8	58.7	32.6	32.6					
23 V	5465.1	626.7	519.8	512.1	66.3	37.2	37.2					
24 Cr	5989.2	695.7	583.8	574.1	74.1	42.2	42.2					
25 Mn	6539.0	769.1	649.9	638.7	82.3	47.2	47.2					
26 Fe	7112.0	844.6	719.9	706.8	91.3	52.7	52.7					
27 Co	7708.9	925.1	793.3	778.1	101.0	58.9	58.9					
28 Ni	8332.8	1008.6	870.0	852.7	110.8	68.0	66.2					
29 Cu	8978.9	1096.7	952.3	932.5	122.5	77.3	75.1					
30 Zn	9658.6	1196.2	1044.9	1021.8	139.8	91.4	88.6	10.2	10.1			



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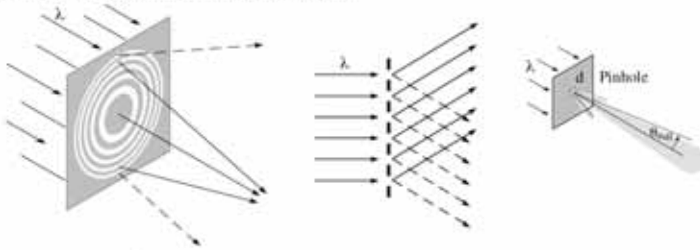
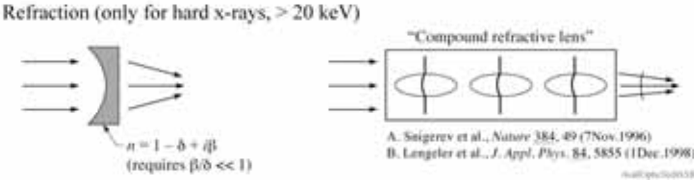
Available x-ray optical techniques

- Reflection (glancing incidence or multilayer coatings)

- Diffraction (zone plates, gratings, pinholes)



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



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

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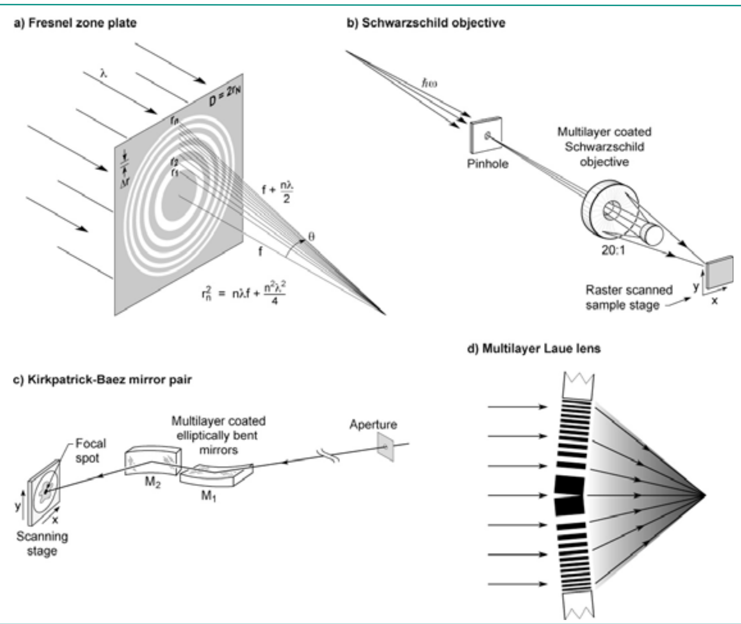
Diffractive and reflective optics for EUV, soft x-rays and hard x-rays



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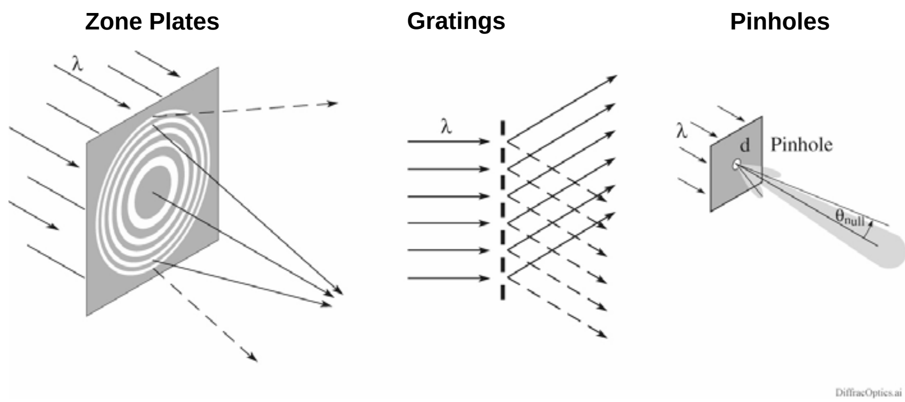
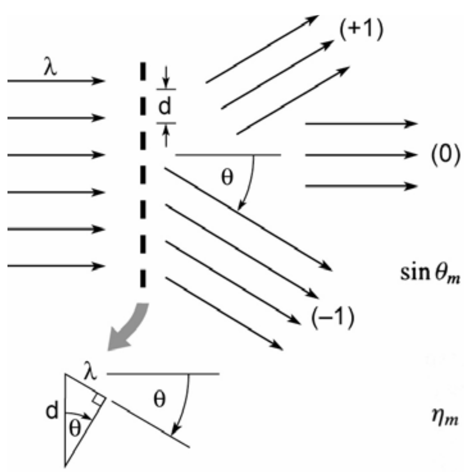
Diffractive optics for soft x-rays and EUV



Diffraction from a transmission grating



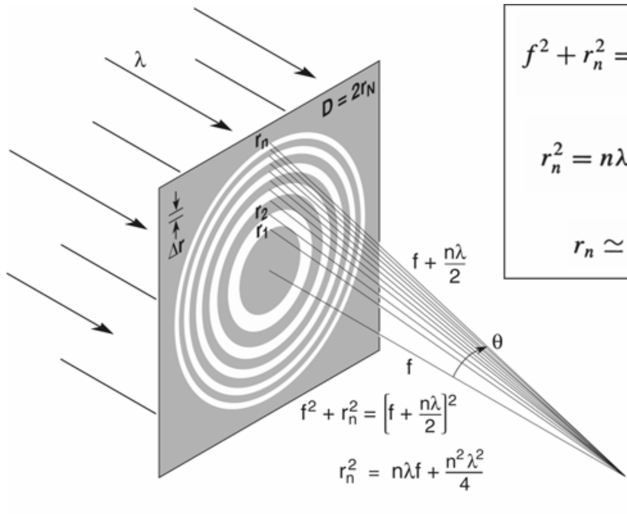
$$\sin\theta_m = \frac{m\lambda}{d}\ ; \quad m = 0,\ \pm1,\ \pm2,\ \pm3,\ldots \quad (9.2)$$

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

(50% absorbed)

Ch09_F03VGrev.4.04.ai

A Fresnel zone plate lens



$$f^2 + r_n^2 = \left(f + \frac{n\lambda}{2}\right)^2 \qquad (9.8)$$

$$r_n^2 = n\lambda f + \frac{n^2\lambda^2}{4} \qquad (9.9)$$

$$r_n \simeq \sqrt{n\lambda f} \qquad (9.10)$$

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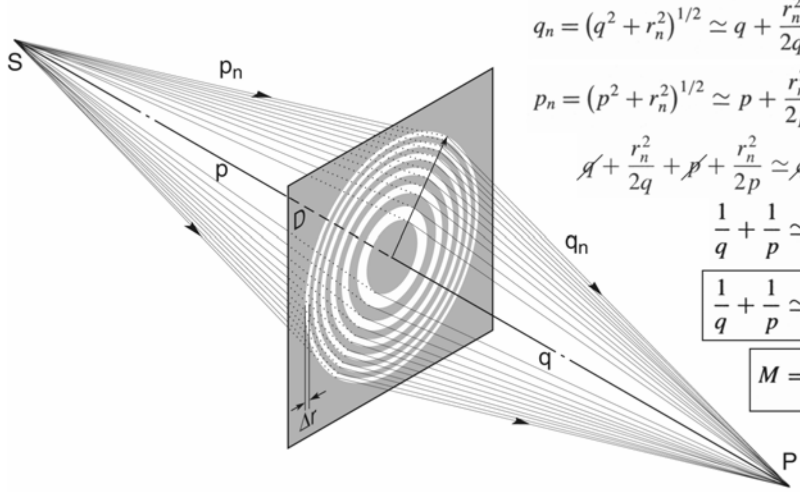
A Fresnel zone plate lens used as a diffractive lens for point to point imaging



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

$$q_n = (q^2 + r_n^2)^{1/2} \simeq q + \frac{r_n^2}{2q}$$

$$p_n = (p^2 + r_n^2)^{1/2} \simeq p + \frac{r_n^2}{2p}$$

$$\not{q} + \frac{r_n^2}{2q} + \not{p} + \frac{r_n^2}{2p} \simeq \not{q} + \not{p} + \frac{n\lambda}{2}$$

$$\frac{1}{q} + \frac{1}{p} \simeq \frac{n\lambda}{r_n^2}$$

$$\boxed{\frac{1}{q} + \frac{1}{p} \simeq \frac{1}{f}} \qquad (9.17)$$

$$\boxed{M = \frac{p}{q}} \qquad (9.18)$$

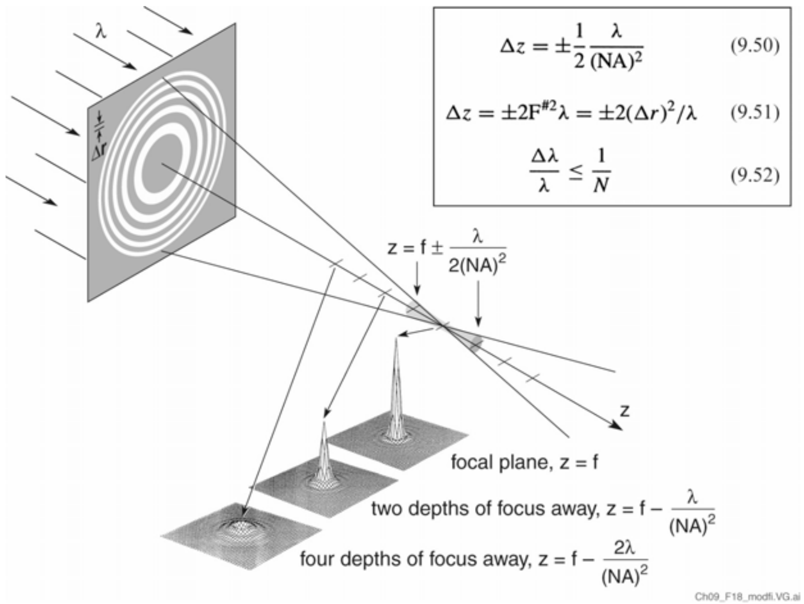
Ch09_F02_modif.VG.ai

Depth of focus and spectral bandwidth

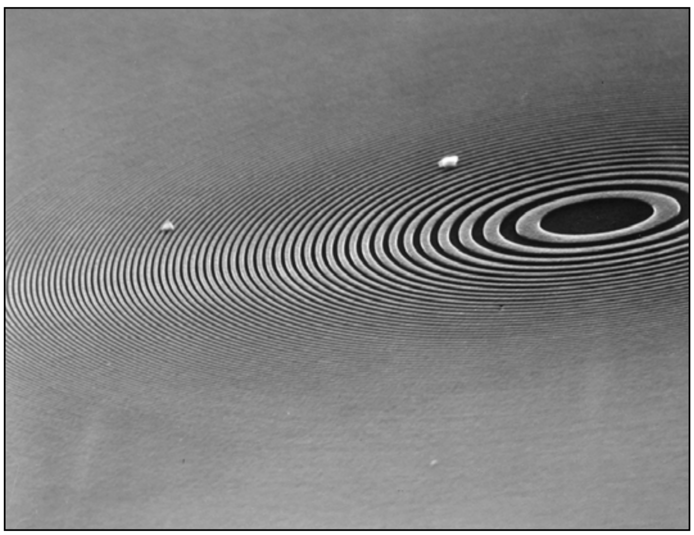
$$\Delta z = \pm \frac{1}{2} \frac{\lambda}{(\mathrm{NA})^2} \qquad (9.50)$$

$$\Delta z = \pm 2\mathrm{F}^{\#2}\lambda = \pm 2(\Delta r)^2/\lambda \qquad (9.51)$$

$$\frac{\Delta\lambda}{\lambda} \le \frac{1}{N} \qquad (9.52)$$



A Fresnel zone plate lens for soft x-ray microscopy

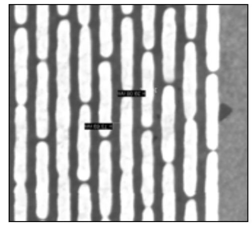


Courtesy of E. Anderson, LBNL

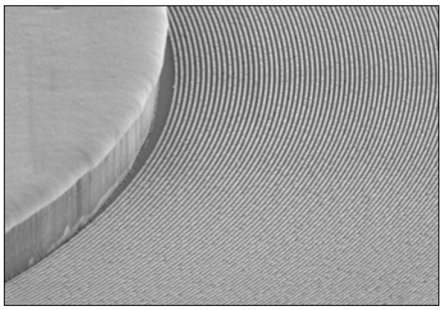
Zone plates for ALS STXM beamlines – "3D Engineered Nanostructures"

Δr = 35 nm, Δt = 180 nm Au, N = 1700
D = 240 μm, 3 x 95 μm^D central stop

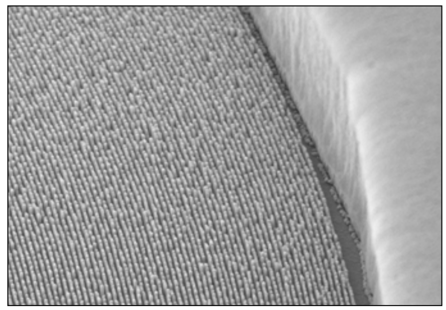
Outer zone close-up



Inner zones



Outer zones



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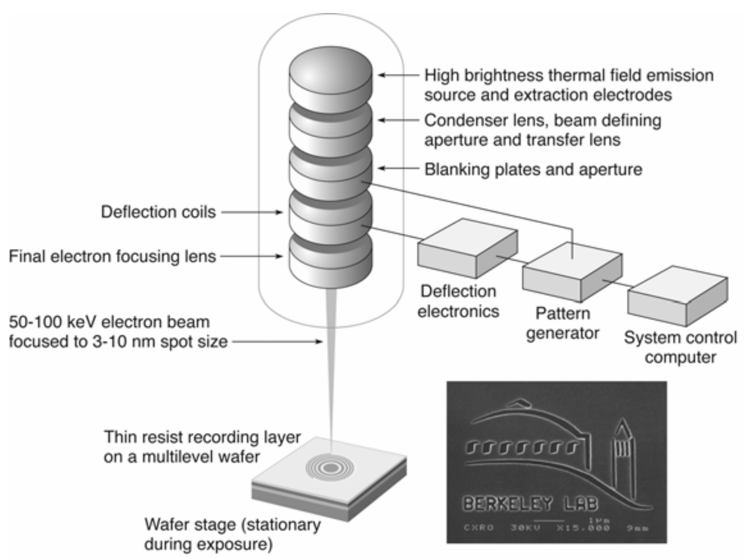
The Nanowriter: high resolution electron beam writing with high placement accuracy



Courtesy of E. Anderson (LBNL)

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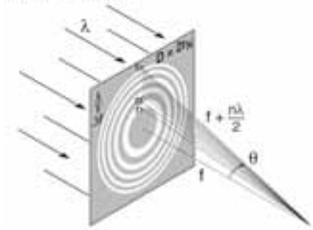
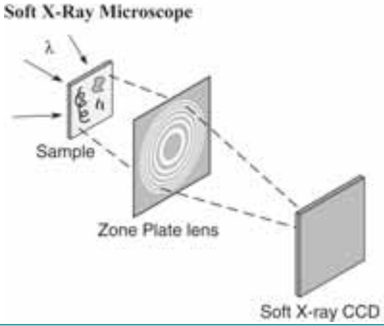
Zones plates for soft x-ray image formation

Zone Plate Lens



Soft X-Ray Microscope



Zone Plate Formulae

$r_n^2 = n\lambda f + \frac{n^2\lambda^2}{4}$	(9.9)	$\lambda = 2.5$ nm, $\Delta r = 25$ nm, $N = 618$
$D = 4N\Delta r$	(9.13)	63 μm
$f = \frac{4N(\Delta r)^2}{\lambda}$	(9.14)	0.63 mm
$NA = \frac{\lambda}{2\Delta r}$	(9.15)	0.05
$\text{Res.} = k_1 \frac{\lambda}{\text{NA}} = 2k_1\Delta r$	$k_1 = 0.61$ $(\sigma = 0)$	$1.22\Delta r = 30$ nm
	$k_1 = 0.4$ $(\sigma = 0.45)$	$0.8\Delta r = 19$ nm
$\text{DOF} = \pm \frac{1}{2} \frac{\lambda}{(\text{NA})^2}$	(9.50)	1 μm
$\frac{\Delta\lambda}{\lambda} \leq \frac{1}{N}$	(9.52)	1/700

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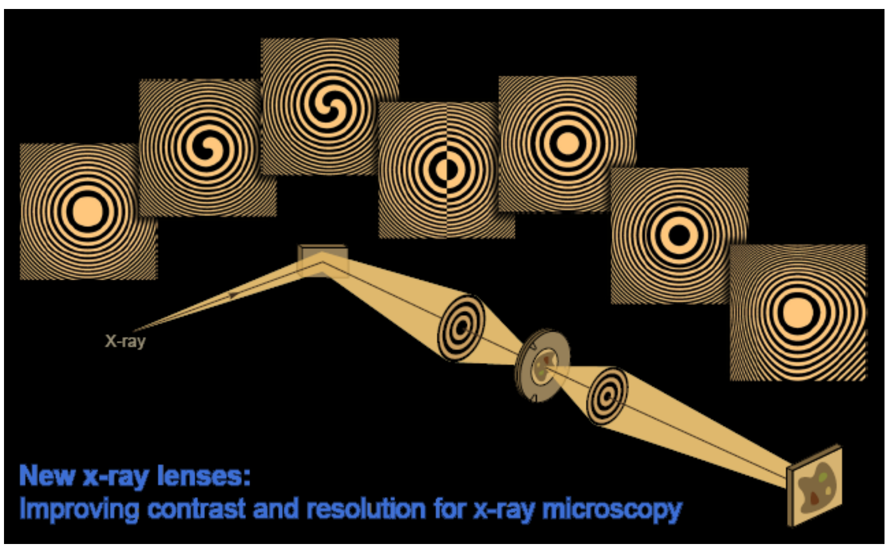
New x-ray lenses: Improving contrast and resolution for x-ray microscopy



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

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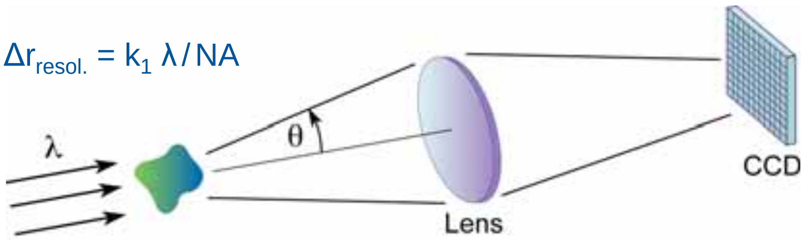
Diffraction limited x-ray imaging

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

$\Delta r_{resol.} = k_1 \lambda / NA$



where NA = n sinθ and the constant k_1 depends on illumination and specific image modulation criteria.
For x-rays

$$n = 1 - \delta + i\beta \qquad \delta, \beta << 1$$

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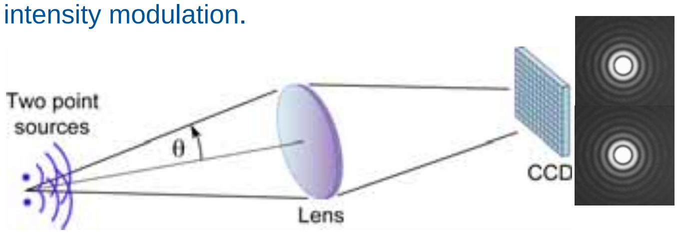
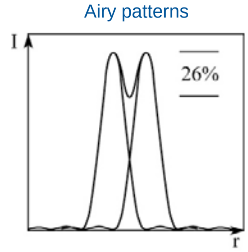
Diffraction limited x-ray imaging

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



λ = 2.48 nm
(500 eV)

Two overlapping
Airy patterns



$\Delta r_{resol.} = 0.61 \lambda / NA$

Resultant intensity pattern when the two point sources are "just resolved", such that the central lobe maximum due to one point source overlaps the first minimum (dark ring) of the other.

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

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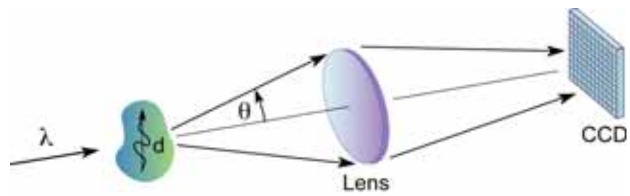
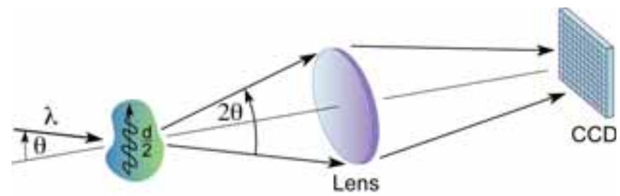
Resolution and illumination

Achievable resolution can be improved by varying illumination:

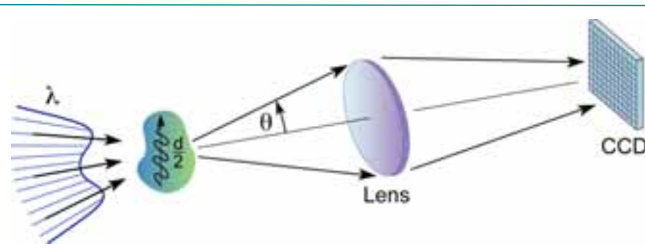
An object pattern of periodicity d diffracts light and is just captured by the lens – setting the diffraction limited resolution limit.



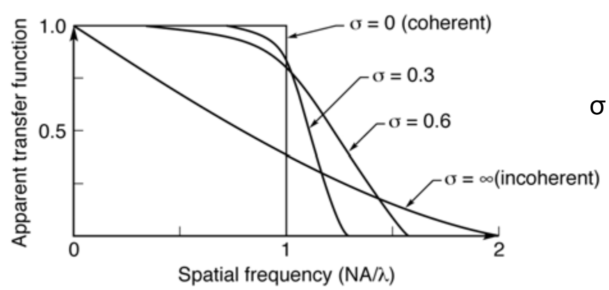
Diffraction from an object of smaller periodicity, d/2, is just captured, and resolved, when illuminated from an angle.



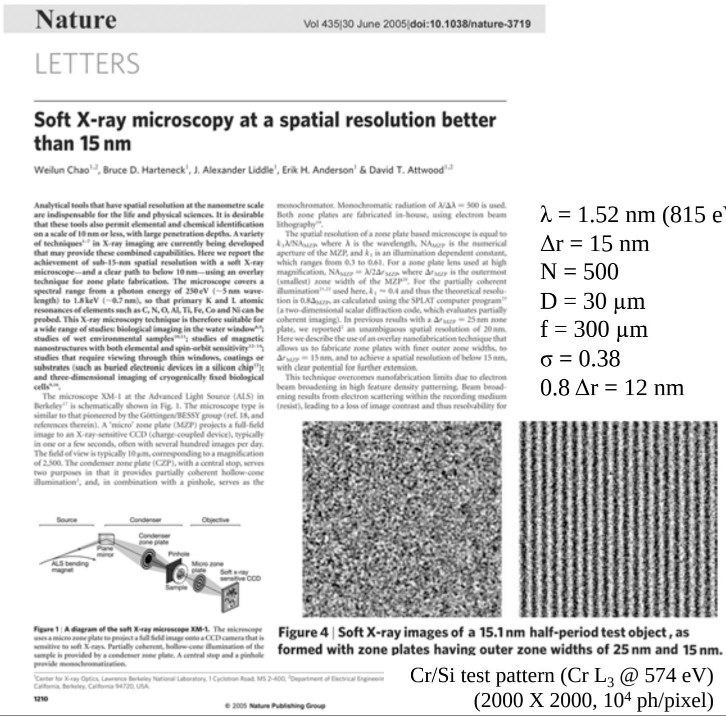
Resolution, illumination, and optical transfer function



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



$$\sigma = \frac{NA_{cond}}{NA_{obj}} \qquad (10.3)$$



Nature   Vol 435|30 June 2005|doi:10.1038/nature-3719

LETTERS

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

Weilun Chao[1,2], Bruce D. Harteneck[1], J. Alexander Liddle[1], Erik H. Anderson[1] & David T. Attwood[1,2]

Figure 1 | A diagram of the soft X-ray microscope XM-1.

Figure 4 | 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.

λ = 1.52 nm (815 eV)
Δr = 15 nm
N = 500
D = 30 μm
f = 300 μm
σ = 0.38
0.8 Δr = 12 nm

Cr/Si test pattern (Cr L_3 @ 574 eV)
(2000 X 2000, 10^4 ph/pixel)

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Hard x-ray zone plate microscopy

- 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.

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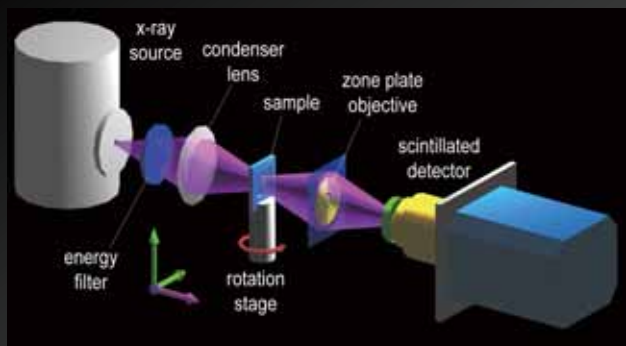
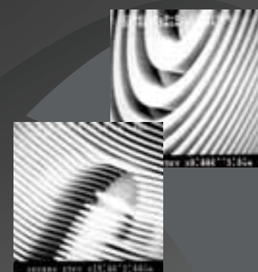
Nanoscale hard x-ray tomography



X-ray Zone-plate Lens



Challenges for achieving nm scale resolution:

- High resolution objective lens: limiting the ultimate resolution
- High numerical aperture condenser lens:
- Detector: high efficiency for lab. source and high speed for synchrotron sources
- Precision mechanical system

Courtesy of Wenbing Yun and Michael Feser, Xradia

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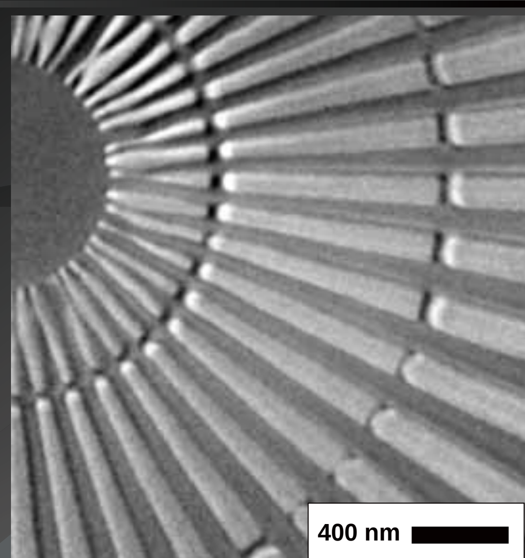
Xradia nanoXCT: Sub-25 nm Hard X-ray Image

Xradia Resolution Pattern
- 50 nm bar width
- 150 nm thick Au
- 8keV x-ray energy
- 3rd diffraction order

F. Duewer, M. Tang,
G. C. Yin, W. Yun,
M. Feser, et al.

Xradia nano-XCT
8-50S installed at
NSRRC, Taiwan



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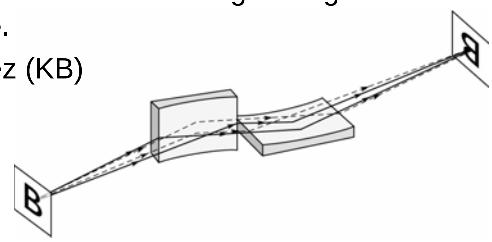
Hard x-ray imaging based on glancing incidence reflective optics

- 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



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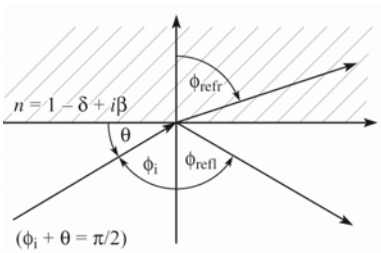
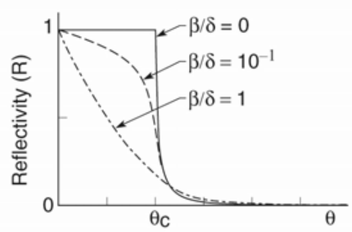
Glancing incidence optics





Snell’s Law: $\sin\phi_{refr.} = \dfrac{\sin\phi_i}{n}$

Total external Reflection:

$$\phi_{refr.} \to \frac{\pi}{2} \quad \text{as } \phi_i \to \phi_{critical}$$

$$\text{Snell's Law: } 1 = \frac{\sin\phi_c}{1-\delta}$$

$$\sin(90^\circ - \theta_c) = 1 - \delta$$

$$\cos\theta_c = 1 - \delta$$

$$1 - \frac{\theta_c^2}{2} = 1 - \delta$$

$$\theta_c = \sqrt{2\delta}$$

For gold at 1 keV

$$\delta = 2.1 \times 10^{-3}$$

$$\theta_c = 3.7^\circ$$

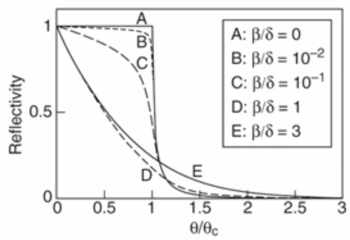
(www.cxro.LBL.gov ; “X-ray properties of the elements” “X-ray interaction with matter”)

GlancngIncidncOptics.ai

CheironSchool_Sept2012_Lec1.ppt 32

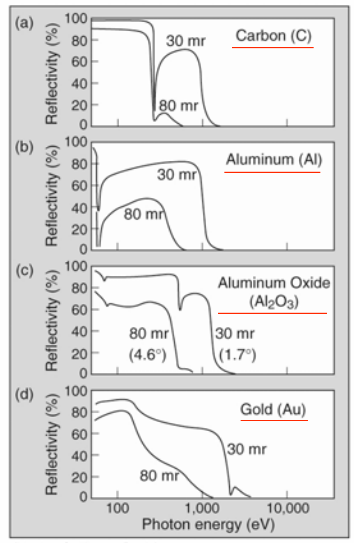
Total external reflection with finite β

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



(Henke, Gullikson, Davis)

Ch03_TotalExtrnlReflc3.ai

Normal incidence reflection at an interface

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

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 ($\phi = 0$):

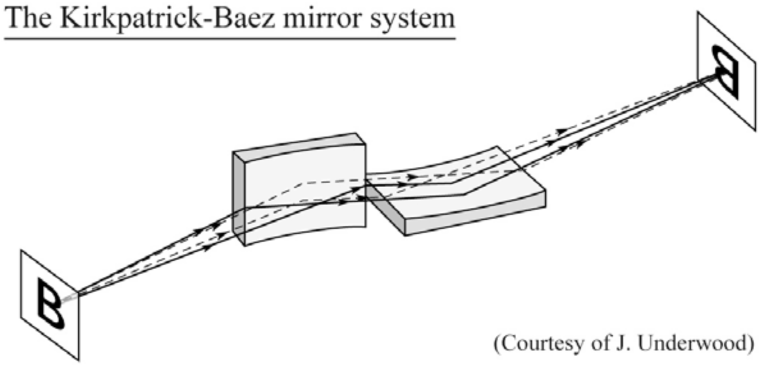
$$R_{s,\perp} \simeq \frac{\delta^2+\beta^2}{4} \qquad (3.50)$$

Example: Nickel @ 300 eV (4.13 nm)
$f_1^0 = 17.8$ $\quad f_2^0 = 7.70$
$\delta = 0.0124$ $\quad \beta = 0.00538$
$R_\perp = 4.58 \times 10^{-5}$

Ch03_NormIncidReflc_5.05.ai

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

Ch03_FocusCurv_Sept2010.ai

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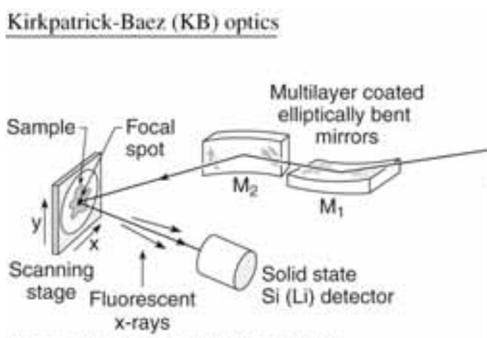
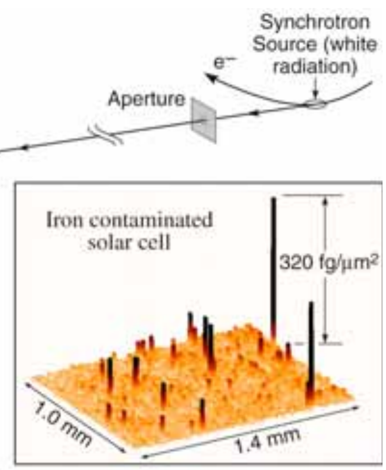
Fluorescent microprobe based in crossed cylinders

Kirkpatrick-Baez (KB) optics



(Courtesy of A. Thompson and J. Underwood, LBNL; and R. Holm, Miles Lab)



- 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.

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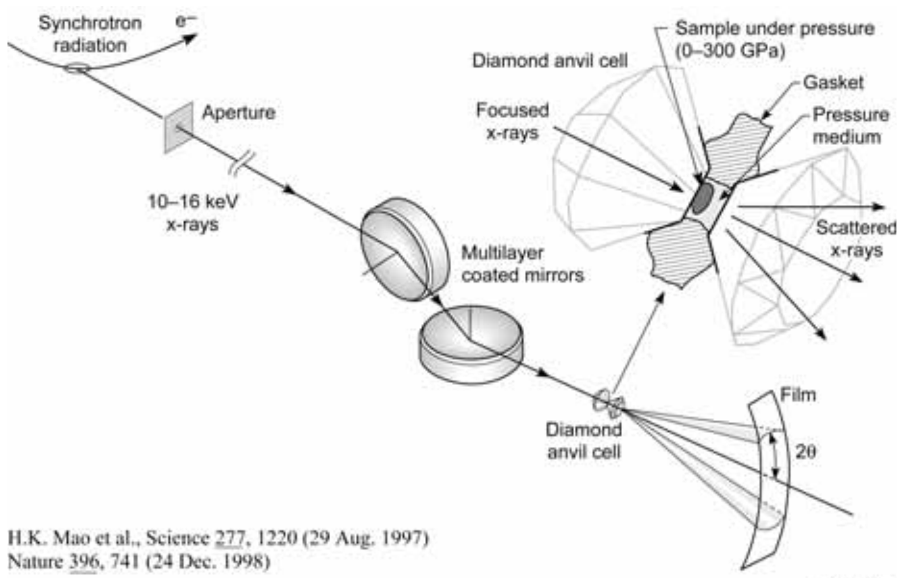
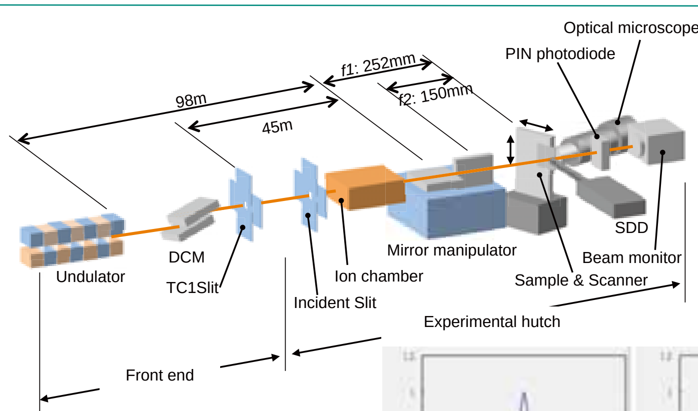
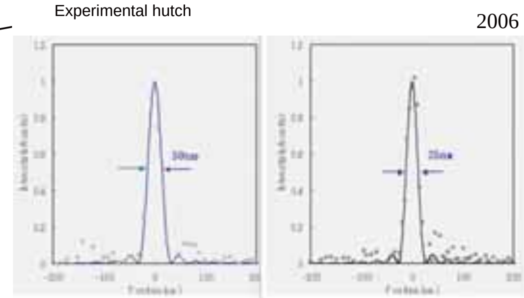
High resolution x-ray diffraction under high pressure using multilayer coated focusing optics



H.K. Mao et al., Science 277, 1220 (29 Aug. 1997)
Nature 396, 741 (24 Dec. 1998)

X-ray microprobe at SPring-8

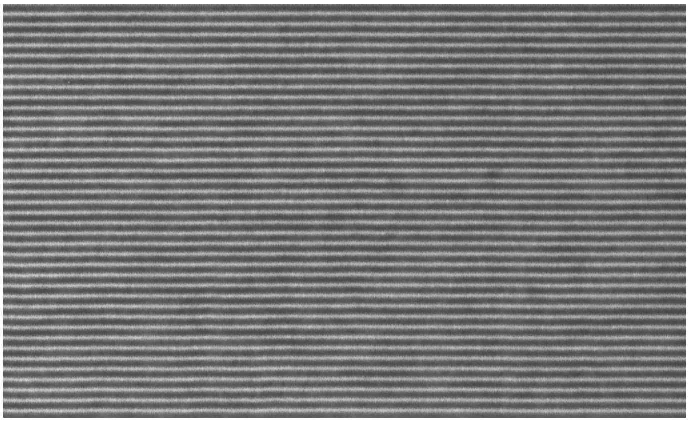




Courtesy of K. Yamauchi and H. Mimura, Osaka University.

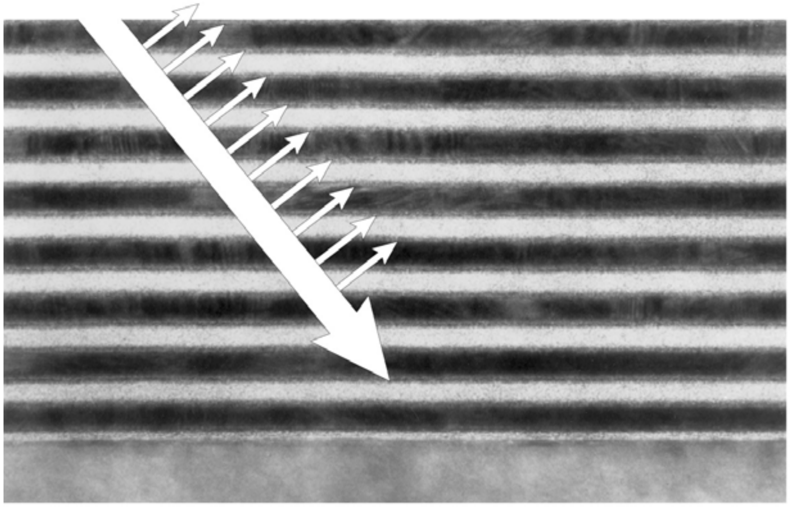
A high quality Mo/Si multilayer mirror

N = 40
d = 6.7



Courtesy of Saša Bajt (LLNL)

Scattering by density variations within a multilayer coating

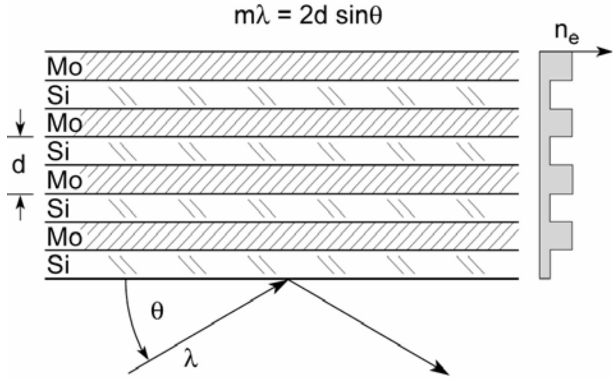


(T. Nguyen, CXRO/LBNL)

Ch04_F01_Feb2007.ai

Multilayer mirrors satisfy the Bragg condition

$$m\lambda = 2d \sin\theta$$



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

$$\lambda = 2d$$
$$d = \lambda/2$$

if the two layers are approximately equal

$$\Delta t \simeq \lambda/4$$

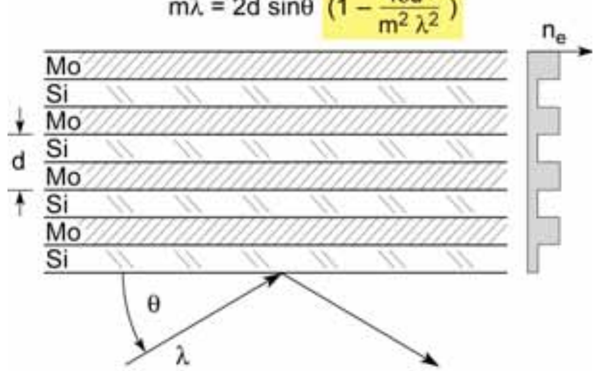
a quarter-wave plate coating.

Ch04_MltlyrMirBragg1.ai

CheironSchool_Sept2012_Lec1.ppt 41

Multilayer mirrors satisfy the Bragg condition

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



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

$$\lambda = 2d$$
$$d = \lambda/2$$

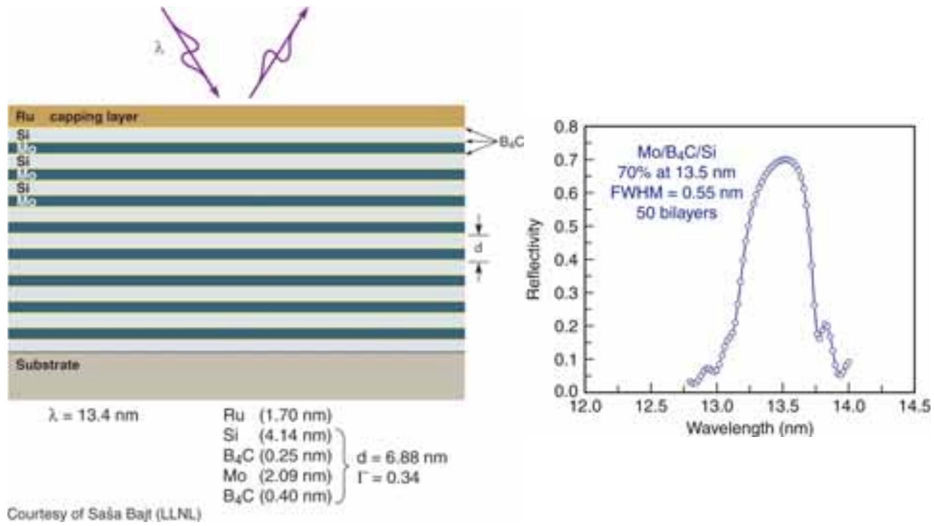
if the two layers are approximately equal

$$\Delta t \simeq \lambda/4$$

a quarter-wave plate coating.

CheironSchool_Sept2012_Lec1.ppt 42

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

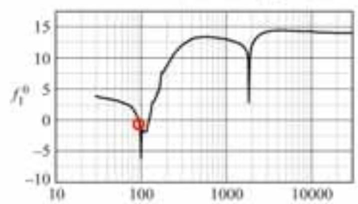


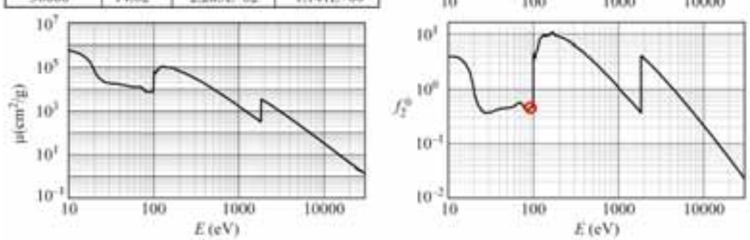
Atomic scattering factors for silicon (Z = 14)

σ_a(barns/atom) = μ(cm^2/g) × 46.64
E(keV)μ(cm^2/g) = f_2^0 × 1498.22

Silicon (Si)
Z = 14
Atomic weight = 28.086

Energy (eV)	f_1^0	f_2^0	μ(cm^2/g)
30	3.799	3.734E−01	1.865E+04
70	2.448	5.701E−01	1.220E+04
100	−5.657	4.580E+00	6.862E+04
300	12.00	6.439E+00	3.216E+04
700	13.31	1.951E+00	4.175E+03
1000	13.00	1.070E+00	1.602E+03
3000	14.23	1.961E+00	9.792E+02
7000	14.33	4.240E−01	9.075E+01
10000	14.28	2.135E−01	3.199E+01
30000	14.02	2.285E−02	1.141E+00





Edge Energies: K 1838.9 eV L$_1$ 149.7 eV
L$_2$ 99.8 eV
L$_3$ 99.2 eV

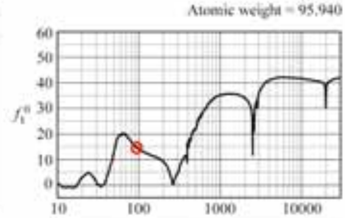
(Henke and Gullikson; www-cxro.LBL.gov)

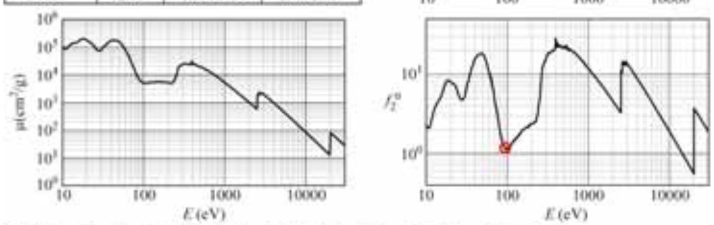
Atomic scattering factors for molybdenum (Z = 42)

σ_a(barns/atom) = μ(cm^2/g) × 159.31
E(keV)μ(cm^2/g) = f_2^0 × 438.59

Molybdenum (Mo)
Z = 42
Atomic weight = 95.940

Energy (eV)	f_1^0	f_2^0	μ(cm^2/g)
30	1.071	5.292E+00	7.736E+04
70	19.38	4.732E+00	2.965E+04
100	14.02	1.124E+00	4.931E+03
300	4.609	1.568E+01	2.292E+04
700	31.41	1.819E+01	1.140E+04
1000	35.15	1.188E+01	5.210E+03
3000	35.88	1.366E+01	1.997E+03
7000	42.11	3.493E+00	2.189E+02
10000	41.67	1.881E+00	8.248E+01
30000	42.04	1.894E+00	2.769E+01





Edge Energies: K 19999.5 eV; L_1 2865.5 eV, L_2 2625.1 eV, L_3 2520.2 eV; M_1 506.3 eV, M_2 411.6 eV, M_3 394.0 eV, M_4 231.1 eV, M_5 227.9 eV; N_1 63.2 eV, N_2 37.6 eV, N_3 35.5 eV

(Henke and Gullikson; www-cxro.LBL.gov)

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CXRO Web Site

X-Ray Interactions with Matter . Search CXRO

Facilities
Publications
Research
X-Ray Tools
Visitors
Personnel
Comments?
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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

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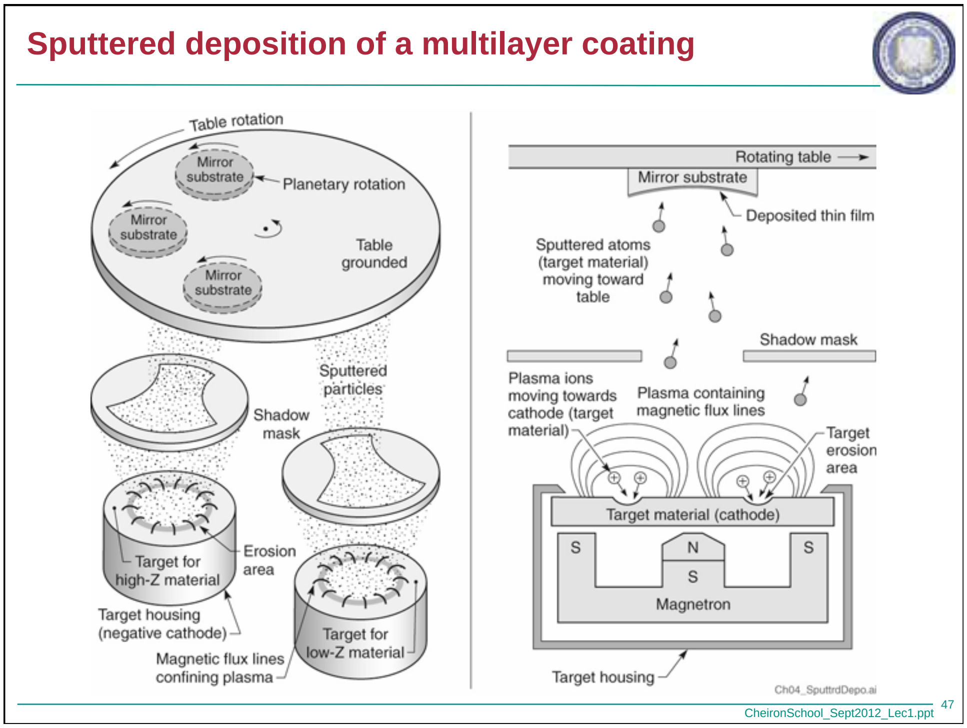
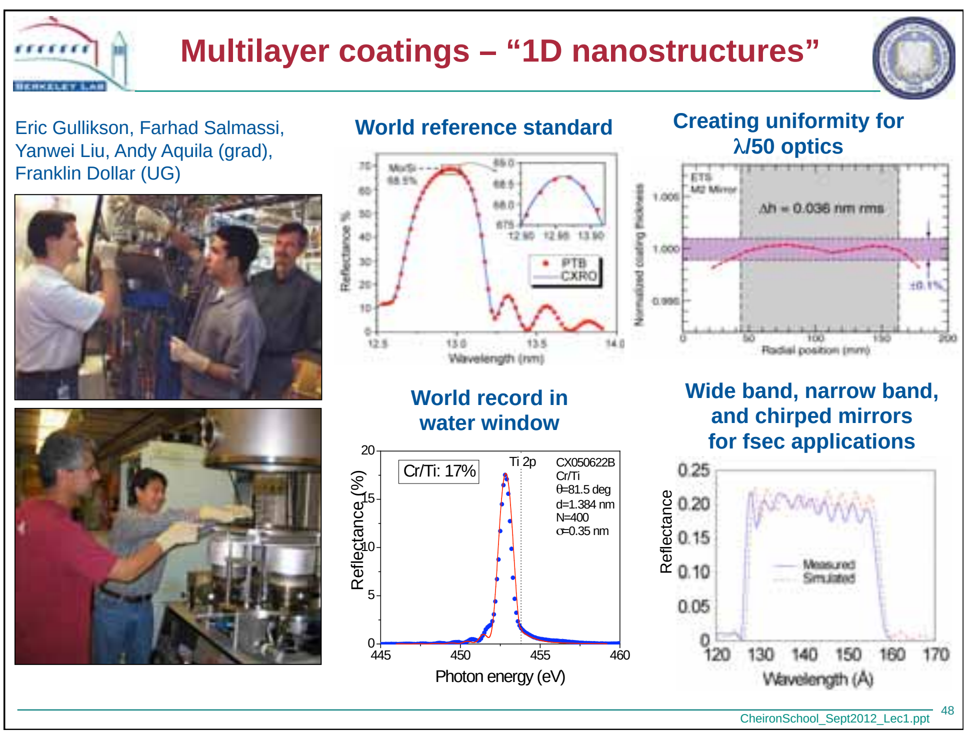
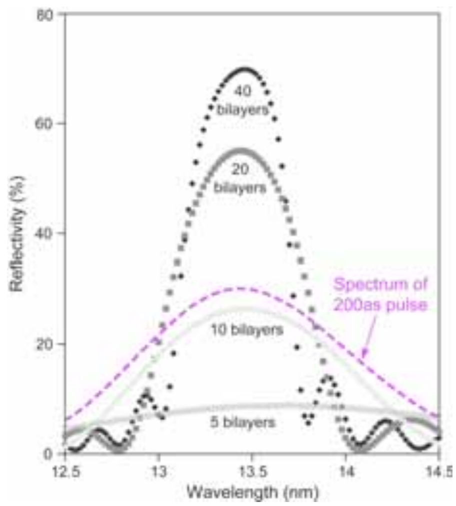

Sputtered deposition of a multilayer coating
Table rotation
Mirror substrate
Planetary rotation
Mirror substrate
Table grounded
Mirror substrate
Sputtered particles
Shadow mask
Erosion area
Target for high-Z material
Target housing (negative cathode)
Magnetic flux lines confining plasma
Target for low-Z material
Rotating table
Mirror substrate
Deposited thin film
Sputtered atoms (target material) moving toward table
Shadow mask
Plasma ions moving towards cathode (target material)
Plasma containing magnetic flux lines
Target erosion area
Target material (cathode)
S
N
S
S
Magnetron
Target housing
Ch04_SputtrdDepo.ai
CheironSchool_Sept2012_Lec1.ppt
47


Multilayer coatings – "1D nanostructures"
Eric Gullikson, Farhad Salmassi, Yanwei Liu, Andy Aquila (grad), Franklin Dollar (UG)
World reference standard
Wavelength (nm)
PTB
CXRO
Creating uniformity for λ/50 optics
Δh = 0.036 nm rms
Radial position (mm)
World record in water window
Cr/Ti: 17%
Ti 2p
CX050622B
Cr/Ti
θ=81.5 deg
d=1.384 nm
N=400
σ=0.35 nm
Reflectance (%)
Photon energy (eV)
Wide band, narrow band, and chirped mirrors for fsec applications
Reflectance
Measured
Simulated
Wavelength (Å)
CheironSchool_Sept2012_Lec1.ppt
48

Broad bandwidth mirrors needed for as/fs pulses

$\Delta E(eV) \cdot \Delta\tau(fs) \geq 1.8\ fs \cdot eV$ (FWHM)



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

Attosecond pulse

→ Broad bandwidth

→ Limited number of layers

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

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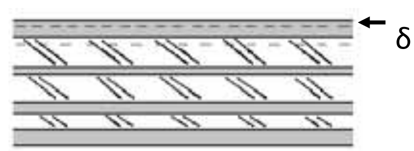
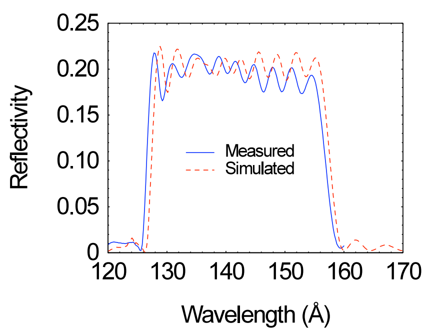
Aperiodic multilayers for asec application

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

A. L. Aquila, F. Salmassi, F. Dollar, Y. Liu, and E. Gullikson, "Developments in realistic design for aperiodic Mo/Si multilayer mirrors," Opt. Express ***14,*** *10073-10078 (2006)*

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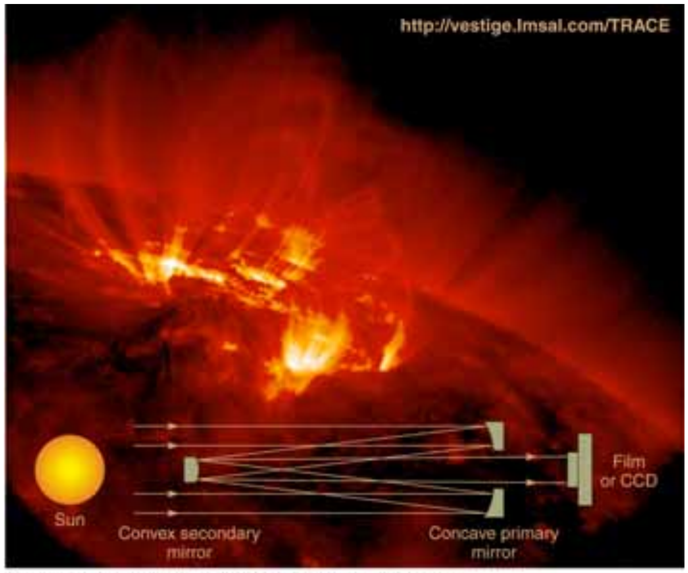
The Cassegrain Telescope with multilayer coatings for EUV imaging of the solar corona



(Photo courtesy of L.Golub, Harvard-Smithsonian and T. Barbee, LLNL)

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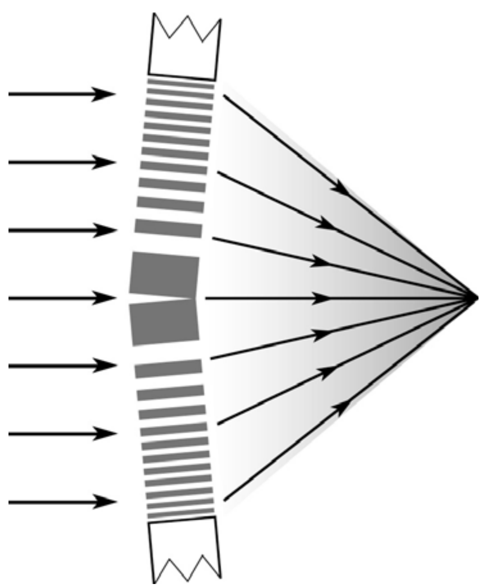
Multilayer Laue Lens for focusing hard x-rays



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Photon energy, wavelength, power

$$\hbar\omega \cdot \lambda = hc = 1239.842 \text{ eV nm} \qquad (1.1)$$

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

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

Ch01_Eqs1.1_2.ai

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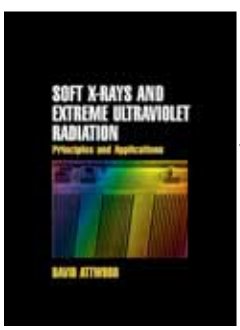
Lectures online at www.youtube.com



Amazon.com

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

CheironSchool_Sept2012_Lec1.ppt 54