Multilayer interference coatings

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

(W/C, T. Nguyen)

Normal incidence reflectivity

Photon energy

10 eV

100 eV

1 KeV

10 KeV

100 nm

10 nm

1 nm

0.1 nm

MgF\(_2\)/Al

Si C

Multilayer mirrors (●)

Pt, Au

Natural crystals

D. Windt, D. Stearns, J. Kortright

Ch4_F00_Feb2007.ai
Scattering by density variations within a multilayer coating

(T. Nguyen, CXRO/LBNL)
Scattering of radiation by a sinusoidal density distribution (atoms or electrons)
Scattering from density variations

In the long wavelength limit ($\lambda \gg a_0$)

\[
J^0(r, t) = -ef^0(\omega)n_a(r, t)\nu(r, t)
\]

\[
J_{\text{scatter}}e^{-i(\omega_s t - k_s \cdot r)} = -ef^0(\omega_i)n_a e^{-i(\omega_r t - k_d \cdot r)} \frac{-eE_i}{-i\omega m} e^{-i(\omega_t t - k_i \cdot r)}
\]

\[
J_s = \frac{i e^2 n_a f^0(\omega_i)}{\omega_i m} E_i
\]

\[
\omega_s = \omega_i + \omega_d
\]

\[
k_s = k_i + k_d
\]

\[
\hbar \omega_s = \hbar \omega_i + \hbar \omega_d
\]

\[
\hbar k_s = \hbar k_i + \hbar k_d
\]

\[
\sin \theta = \frac{k_d/2}{k_i}
\]

or

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

\[
m\lambda = 2d \sin \theta
\]
Multilayer mirrors satisfy the Bragg condition

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

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

\[
\begin{align*}
\lambda &= 2d \\
d &= \lambda/2
\end{align*}
\]

if the two layers are approximately equal

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

a quarter-wave plate coating.

Ch04_MultilayerMirBragg1.ai
An angular scan of a multilayer mirror performs a Fourier-transform of the density profile.

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

\( \lambda = 2\left(\frac{d}{3}\right)\sin\theta_3 \)

\( \sin\theta_3 = 3\sin\theta_1 \)
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 multilayer coatings require

- Refractive index contrast at the interfaces
- Minimal absorption in the low-Z material
- Thin high-Z layer where possible $\Gamma \equiv \Delta \tau_H / (\Delta \tau_H + \Delta \tau_L)$
- Interfaces which are chemically stable with time
- Minimal interdiffusion at the interfaces
- Minimal interfacial roughness (no crystallite formation within the layers, no shadowing in the coating process, surface mobility)
- Thermal stability during illumination
- Chemically stable vacuum interface (e.g., SiO$_2$ or capping layer)
- Uniform coating thickness
Computed reflectivity of a W/C x-ray multilayer mirror

\( W/C \)
\[ \lambda = 8.34 \, \text{Å} \]
\[ d = 22.5 \, \text{Å} \]
\[ N = 100 \]
\[ \Gamma = 1/3 \]

(Courtesy of J. Underwood and D. Solina)
High order reflections from a multilayer coating

Measured

![Graph showing measured reflectivity](image1)

- W/C multilayer
- 22 layer-pairs
- \(d = 36.1 \text{ Å}\)
- \(\lambda = 1.54 \text{ Å}\)

Calculated internal interference of incoming and outgoing waves

![Graph showing calculated interference](image2)

(Courtesy of Y. Wu and J. Underwood.)
Multilayer interface mirrors computational model

With refractive index \( n \):

(Courtesy of J. Underwood)

www.cxro.LBL.gov
Atomic scattering factors for Silicon (Z = 14)

\[ \sigma_a (\text{barns/atom}) = \mu (\text{cm}^2/\text{g}) \times 46.64 \]
\[ E (\text{keV}) \mu (\text{cm}^2/\text{g}) = f_2^0 \times 1498.22 \]

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<th>Energy (eV)</th>
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<th>( \mu (\text{cm}^2/\text{g}) )</th>
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Silicon (Si)
\[ Z = 14 \]
Atomic weight = 28.086

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)

Prof. David Attwood / UC Berkeley EE213 & AST210 / Spring 2009
Atomic scattering factors for Molybdenum
(Z = 42)

\[ \sigma_{\text{m}}(\text{barns/atom}) = \mu(\text{cm}^2/\text{g}) \times 159.31 \]

\[ E(\text{keV})\mu(\text{cm}^2/\text{g}) = f_2^0 \times 438.59 \]

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Molybdenum (Mo)

\[ Z = 42 \]

Atomic weight = 95.940

(\text{Henke and Gullikson}; \text{www-cxro.LBL.gov})
Optimized reflectivity with thin “high-Z” layers

\[
\Gamma = \frac{\Delta t_H}{\Delta t_H + \Delta t_L} = \frac{\Delta t_H}{d}
\]  \hspace{1cm} (4.7)

\[
\tan(\pi \Gamma_{\text{opt}}) = \pi \left[ \Gamma_{\text{opt}} + \frac{\beta_L}{\beta_H - \beta_L} \right]
\]  \hspace{1cm} (4.8)

(Vinogradov and Zeldovich, 1977)
(also see Borrmann, 1941)

- Sharp interfaces needed for scattering
- Thin high-Z layer to minimize absorption
- Low-Z layer best as a “spacer”
A high quality Mo/Si multilayer mirror

N = 40
d = 6.7 nm

Courtesy of Saša Bajt (LLNL)
Mo/Si multilayer interference coating

Molybdenum as the “scattering layer”

Silicon as the non-absorbing “spacing layer”

Actually an exaggeration, the complex refractive index of each material plays a role in the reflection process.

The absorption edge Si-L3 = 99.2 eV (12.5 nm)

Higher photon energies are absorbed in Si, lower photon energies (longer wavelengths) are not.

Typically $\lambda = 13.4$ nm or more.

Molybdenum has relatively good scattering properties in this photon energy (wavelength) region, with limited absorption.

\[
n_{Si} = 1 - 6.6 \times 10^{-5} + i 1.8 \times 10^{-3} \\
\lambda_{Si} = 12.5 \text{ nm}
\]

\[
n_{Mo} = 0.924 + i 7.4 \times 10^{-3}
\]
High reflectivity, thermally and environmentally robust multilayer coating for high throughput EUV lithography

![Diagram of multilayer coating](image)

- **λ = 13.4 nm**
- **Ru (1.70 nm)**
- **Si (4.14 nm)**
- **B₄C (0.25 nm)**
- **Mo (2.09 nm)**
- **B₄C (0.40 nm)**

**d = 6.88 nm**

**Γ = 0.34**

Courtesy of Saša Bajt (LLNL)
Multilayer mirrors have achieved a reflectivity of 70%
Recent progress in multilayer mirrors

Near-Normal Incidence Multilayer Mirrors

Peak reflectance (%)

Wavelength (nm)

Sc  C  Si

H₂O window

Ti  V  Au
Sputtered deposition of a multilayer coating
DC magnetron sputtering is used to reliably deposit multilayer coatings of predictable center wavelength and excellent uniformity.

Substrates mounted on a rotating platter are swept across each sputter source sequentially to form the multilayer. Modulating the platter velocity provides precision control of radial thickness distribution and absolute film thickness. The substrate is also spun fast about its own axis for azimuthal uniformity.

(Courtesy of Jim Folta, LLNL)
Buried, trace amounts of iron in a defective silicon solar cell

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

(Courtesy of T. Tokunaga; and A. Thompson, LBNL.)
Polarization studies of magnetic materials

(Courtesy of J. Kortright and M. Rice, LBNL; and R. Carr, Stanford)
Photoemission microscopy for surface science and characterization

(Courtesy of F. Cerrina, Univ. Wisconsin, Madison and J. Underwood, CXRO, LBNL, Berkeley)
Photoemission spectroscopy reveals characteristic electron binding energies
Photoemission spectroscopy as a tool for surface science

(Courtesy of M. Olmstead, Univ. Washington, Seattle)

Colorplate XIX
Ch04_PhotoemisSpectr2.ai
Observation of varied chemical states by photoemission spectromicroscopy

Agglomeration of TiSi$_2$ during annealing appears to have exposed SiO$_2$ near the edges of the poly pads.

(Courtesy of S. Singh and F. Cerrina, Univ. Wisconsin, Madison)
Photoemission microscopy of a AlGaN film – “Monet”

(Courtesy of G.-F. Lorusso and F. Cerrina, Univ. Wisconsin, Madison, and Advanced Light Source, Berkeley)
High resolution x-ray diffraction under high pressure using multilayer coated focusing optics

Elasticity and rheology of iron above 220 GPa and the nature of the Earth’s inner core

Ho-kwang Mao, Jinfu Shu, Guoyin Shen, Russell J. Hemley, Baosheng Li & Anil K. Singh

* Geophysical Laboratory and Center for High Pressure Research, Carnegie Institution of Washington, 5251 Broad Branch Road, NW, Washington DC 20015, USA
† Consortium for Advanced Radiation Sources, University of Chicago, Chicago, Illinois 60637, USA
‡ Center for High Pressure Research, Mineral Physics Institute, State University of Stony Brook, Stony Brook, New York 11794-2100, USA
§ Materials Science Division, National Aerospace Laboratories, Bangalore 560017, India

Recent numerical-modelling and seismological results have raised new questions about the dynamics1,2 and magnetism3,4 of the Earth’s core. Knowledge of the elasticity and texture of iron5-8 at core pressures is crucial for understanding the seismological observations, such as the low attenuation of seismic waves, the low shear-wave velocity2,8 and the anisotropy of compressional-wave velocity6-11. The density and bulk modulus of hexagonal-close-packed iron have been previously measured to core pressures by static12 and dynamic13,14 methods. Here we study, using radial X-ray diffraction15 and ultrasonic techniques16, the shear modulus, single-crystal elasticity tensor, aggregate compressional- and shear-wave velocities, and orientation dependence of these velocities in iron. The inner core shear-wave velocity is lower than the aggregate shear-wave velocity of iron, suggesting the presence of low-velocity components or anelastic effects in the core. Observation of a strong lattice strain anisotropy in iron samples indicates a large (~24%) compressional-wave anisotropy under the isostress assumption, and therefore a perfect alignment of crystals would not be needed to explain the seismic observations. Alternatively the strain anisotropy may indicate strain variation due to preferred slip systems.

Probed the lattice strain of the sample as a function of the angle (ψ) to the diamond-cell axis10. At 21 pressures between 16 and 211 GPa, energy dispersive X-ray diffraction (EDXD) patterns containing (hkl) notation16) 100, 002, 101, 102, 110, 113, 112, 201 diffraction lines of hexagonal closed packed (h.c.p.) iron, 111, 200, 220, 311, 222, 400, 331, 420, 422, 511 of gold, or 110, 200, 211, 220, 310, 222, 321, 400 of tungsten, were collected at 10° steps of ψ from 0° to 90°. The d-spacing varies linearly with cos(ψ):

\[ d(hkl) = d_0(hkl)[1 + (1 - 3\cos^2(ψ)Q(hkl))] \]

where the intercept \(d_0(hkl)\) denotes the d-spacing under \(σ_{\text{Au}}\) and the slope \(Q(hkl)\) is the lattice strain under the uniaxial stress condition15,16.

In run 1, a separate gold layer was used as a standard for determination of \(t\) and shear modulus \(G\) of h.c.p. Fe. The axial stress is continuous across the interface between the gold and iron layers \(σ_{\text{Au}} = σ_{\text{Fe}};\) subscripts denote the Au or Fe layer; that is

\[ t_{\text{Fe}} = 1.5(σ_{\text{Fe}} + σ_{\text{Fe}}) = 1.5(σ_{\text{Fe}} + σ_{\text{Fe}}) + t_{\text{Au}} \]

Now, \(t\) is related to \(G\) by

\[ t = 6GQ \]

where \(Q\) denotes the average value of measured \(Q\) for all \((hkl)\) (ref. 15). The hydrostatic stress components, \(σ_{\text{Fe}}\) and \(σ_{\text{Au}}\), were determined from the observed \(d_0(hkl)\) (equation (3)) and the equations of state of Au and Fe (refs 20, 21); \(G_{\text{Au}}\) was extrapolated from low-pressure data22,23. The aggregate compressional-wave speed \(v_p\) and shear-wave speed \(v_s\) of h.c.p. Fe are calculated from the bulk modulus \(K\) and \(G_{\text{Fe}}\). In addition (run 3), the aggregate ultrasonic
The Cassegrain telescope

Sun
Convex secondary mirror
Concave primary mirror
Film or CCD

Ch04_CassegrainTele.ai
Extreme ultraviolet astronomy

The solar corona at 17.3 nm (71.7 eV), observed with a rocket launched Cassegrain telescope using Mo/Si coated mirrors (d = 8.55 nm, Γ = 0.43, 35% at 17.2 nm; Al L-edge filter at 72.5 eV narrows band pass to 17.1-17.5 nm, λ/Δλ = 40). Emission dominated by Fe$^{+8}$ and Fe$^{+9}$ in the 100 eV (1.2 × 10$^6$ K) temperature coronal plasma.

Courtesy of A.B.C. Walker (Stanford), T.W. Barbee (LLNL), R.B. Hoover and J.F. Lindbloom (NASA)
EUV image of the solar corona showing loops near the solar limb

(Courtesy of L. Golub, Harvard-Smithsonian and T. Barbee, LLNL)
Dynamics of the solar corona

(Courtesy of L. Golub, Harvard-Smithsonian)
### Table 3.5. Ionization potentials (electron volts) [1–20].

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Ar-like Fe (26 – 8 = 18)
# ATOMIC AND IONIC SPECTRUM LINES OF HYDROGEN THROUGH KRYPTON

**IRON IX (Fe\(^{8+}\)), Z = 26**

Ground State 1s\(^2\)2s\(^2\)2p\(^6\)3s\(^2\)3p\(^6\)(\(1^3S_0\)) (18 electrons)

Ionization Potential 1 884 000 cm\(^{-1}\); 233.6 eV

<table>
<thead>
<tr>
<th>Multiplet</th>
<th>Rel. Int.</th>
<th>(\lambda_{\text{vac}}) (in Å)</th>
<th>Levels (in 10(^3) cm(^{-1}))</th>
<th>Configurations</th>
<th>Terms</th>
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<th>Notes</th>
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RAYMOND L. KELLY

IRON X (Fe$^{9+}$), $Z = 26$

Ground State $1s^22s^22p^63s^23p^5(^3P_{3/2})$ (17 electrons)

Ionization Potential 2 114 000 cm$^{-1}$; 262.1 eV

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<th>Levels (in 10$^3$ cm$^{-1}$)</th>
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Extreme ultraviolet (EUV) lithography

Reflective mask → Absorber pattern → λ = 13 nm → Multilayer mirror → 4:1 reduction optics, aspheric, multilayer coated → Wafer to record 50 nm or smaller features, over cm² dimensions

50 60 70

Ch04_F11VG.ai
Smooth multilayer coatings are required to minimize wavefront errors in EUV optical systems.

\[
\Delta h = \frac{1}{2\sqrt{5}\sqrt{N_S}} \frac{\lambda}{25}
\]

\[
\frac{\Delta d}{d} = \frac{1}{25\sqrt{5}\sqrt{N_S} N}
\]

- \(\frac{\lambda}{25}\) total rms wavefront error
- \(\Delta h_{\text{rms}} = \Delta s_{\text{rms}}/2\)
- double path in reflection
Multilayer coatings for the ETS projection optics approach production specifications

Systematic d-space variations suggest path to further improvements.

(Courtesy of R. Soufli and E. Spiller, LLNL)
SOFT X-RAY OPTICS

Eberhard Spiller

SPIE (1994)