Interface properties of multilayer mirrors with sub-nanometer layer thicknesses

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The Water Window

• AOI 1.5°
• Sc edge: 3.11 nm

Cr 0.790 nm
Sc 0.784 nm

2.3 nm
4.4 nm
Problem: Limited Reflectivity

Cr/Sc Mirrors show only a fraction of theoretically possible reflectivity at an AOI 1.5°

![Graph showing Cr/Sc EUV Reflectivity](image)
Interface Properties

Roughness (diffuse scattering)

Ideal picture

Interdiffusion (diminished reflectivity)
Mapping Reciprocal Space

Typical angles of incidence: 1° – 7° from normal
**DWBA Modelling**

\[
\frac{d\sigma}{d\Omega_{\text{diffuse}}} = \frac{A\pi^2}{\lambda^4} \sum_{j=1}^{N} \sum_{i=1}^{N} (n_j^2 - n_{j+1}^2)^* (n_i^2 - n_{i+1}^2) \left( (T_j^{(1)} + R_j^{(1)})^* (T_j^{(2)} + R_j^{(2)})^* \right.
\]

\[
\times (T_i^{(1)} + R_i^{(1)})(T_i^{(2)} + R_i^{(2)}) \left( c_{ij}^i(q_x) C(q_x) \right)
\]

**Power Spectral Density (PSD)**

Multilayer Factor

**Electric Field Intensities:**

\[
E_t^{(j)}(z) = T_j e^{ik_z^{(j)} z}
\]

\[
E_r^{(j)}(z) = R_j e^{-ik_z^{(j)} z}
\]

Knowledge of the electric field intensities, i.e. multilayer structure (electron density profile) is essential!

Roughness Model

Vertical Correlation Function:

\[
C(q_x) = \frac{4\pi H \sigma^2 \xi^2}{(1 + |q_x|^2 \xi^2)^{1+H}}
\]

\(H\) : Hurst factor, jaggedness of surface

\(\sigma\) : root mean square roughness

\(\xi\) : lateral correlation length

\(c_{ij}^{\perp}(q_x) = \exp\left(-\sum_{n=\min(i,j)}^{\max(i,j)} d_n / \xi^{\perp}(q_x)\right)\)

\(\xi^{\perp}(q_x) = \frac{\xi}{q_x^2}\) : vertical correlation length

\(d_n\) : thickness of \(n\)th layer

Binary Layer Approach

Cr/Sc \( D = 1.5736 \text{ nm} \), \( N = 400 \) EUV Reflectivity

- measured reflectivity
- fit (binary model)

Graded interface model needed!

Binary Model with only Nevot/Croce damping factor fails
Analysis Strategy

Parameters:
• Multilayer period $D$
• Sc and Cr layer thicknesses
• Interdiffusion/mixing of the two materials
• Interface properties/shape
• Nevot/Croce factor (roughness)

Combination of complementary methods:
• EUV reflectivity (EUV)
• Cu K-α XRR
• Resonant EUV reflectivity (across Sc L-edge) (REUV)
• X-ray fluorescence analysis (X-ray standing wave, XSW)

➡ Combined fit based on particle swarm optimization
• Sensitivity for Sc content and total layer thickness D
• 50 % Sc, 50 % Cr
X-ray Standing Wave

- Sensitivity for spacial Sc/Cr distribution
EUV and X-ray Reflectivity

- Sensitivity for total layer thickness $D$ and interface asymmetry

**Cr/Sc:** $D = 1.5736$ nm, $N = 400$ EUV Reflectivity

**XRR:** $E = 8048$ eV
Combined Fit

**EUV**

$E = 5500 \text{ eV}$

$E = 6250 \text{ eV}$

**XSW**

$E = 6250 \text{ eV}$

**XRR**

$E = 8048 \text{ eV}$

Reflectivity across Sc L-edge

**REUV**

Cr/Sc $D = 1.5736 \text{ nm}$, $N = 400$ EUV Reflectivity

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**PTB**
Consistent Model

The two layers interdiffuse strongly (60 %)
Asymmetric interface gradients
“Undisturbed system” for DWBA analysis
B$_4$C as Diffusion Barrier

- EELS measurements suggest B diffusion into Cr layer and C diffusion into Sc layer (Prasciolu et al.: *Appl. Optics* 53, No. 10)

Treat as effective two layer system:

\[
w \cdot n_C + (1-w) \cdot n_{Sc}
\]

\[
w \cdot n_B + (1-w) \cdot n_{Cr}
\]
**Combined Fit**

\[ E = 5500 \text{ eV} \]

\[ E = 6250 \text{ eV} \]

**XSW**

\[ E = 6250 \text{ eV} \]

- **data**
- **fit**

**XRR**

\[ E = 8048 \text{ eV} \]

**REUV**

- **Cr/B_{4}C/Sc**
  \[ D = 1.5649 \text{ nm}, N = 300 \]
  - EUV
  - Reflectivity across Sc L-edge

**Reflectivity across Sc L-edge**

- **log reflectivity**
  \[ \log_{10}(I/I_0) \]

- **Wavelength**
  \[ \text{nm} \]

- **AOI**
  \[ ^\circ \]
• Similar interdiffusion is observed for both systems
• Interface profiles are less asymmetric with B$_4$C
**Diffuse Scattering**

**Best model:**

- **Cr/Sc**  \( \sigma = 0.18 \text{ nm}, \ \bar{\xi} = 4.0 \text{ nm} \)
- **Cr/B_4C/Sc**  \( \sigma = 0.13 \text{ nm}, \ \bar{\xi} = 4.5 \text{ nm} \)
- \( H = 1.0 \)

**Equation:**

\[
C'(q_x) = \frac{4\pi H \sigma^2 \bar{\xi}^2}{(1 + |q_x|^2 \bar{\xi}^2)^{1+H}}
\]
Summary and Outlook

• The combination of several complementary methods are required to deduct a reliable model
• Ultra-thin multilayer systems require explicit modeling of the interfaces showing strong interdiffusion
• Effective power spectral density (roughness) can be extracted by DWBA simulations based on the explicit model found above
Multilayer Mirror Principle

\[ q_z = \frac{2\pi}{\lambda} (\sin \Theta_f + \sin \Theta_i) \quad \frac{q_z = 2\pi/(\bar{n}d)}{\Theta_i = \Theta_f} \quad \lambda = 2\bar{n}d \sin(\Theta_i) \]

\[ q_z = \frac{2\pi}{\lambda} (\sin \Theta_f + \sin \Theta_i) \]

\[ \Theta_i = \Theta_f \]

\[ \lambda = 2\bar{n}d \sin(\Theta_i) \]

\[ d = 7 \text{ nm} \]
Roughness vs. Diffusion

Roughness extracted from diffuse scattering does not suffice to explain low reflectivity

\[ \sigma_D: \text{mean diffusion/roughness} \]
\[ \sigma_R: \text{mean roughness only} \]

\[ \sigma_D = 0.274 \text{ nm} \]
\[ \sigma_R = 0.101 \text{ nm} \]

In contrast to Mo/B\textsubscript{4}C/Si multilayers, roughness is not the primary cause for reflectivity loss
Dynamic Resonances

\[
\frac{2\pi}{\lambda} \sin \Theta_i = \frac{\pi m_K}{D}
\]

\[
\frac{2\pi}{\lambda} \sin \Theta_f = \frac{\pi m_K}{D}
\]

\[
\frac{\Delta}{\lambda}\n
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\frac{\Delta}{\lambda}\n
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Diffusion Barrier $B_4C$

- $B_4C$ improves thermal stability and reduces roughness
- Diffusion increases upon $B_4C$ deposition

- All samples show similarly high roughness correlation laterally and vertically
SX700 Beamline @ BESSY II

- Bending magnet beamline
- Plane grating monochromator: 0.7 nm – 30 nm
- meV energy resolution (down to a few pm)
Outline

Part 1:
• Motivation for Mo/Si multilayer mirrors
• Roughness and diffusion
• Diffuse scattering
• Quantitative analysis: DWBA based model

Part 2:
• Cr/Sc mirrors for the water window