Interface properties of multilayer mirrors with sub-nanometer layer thicknesses

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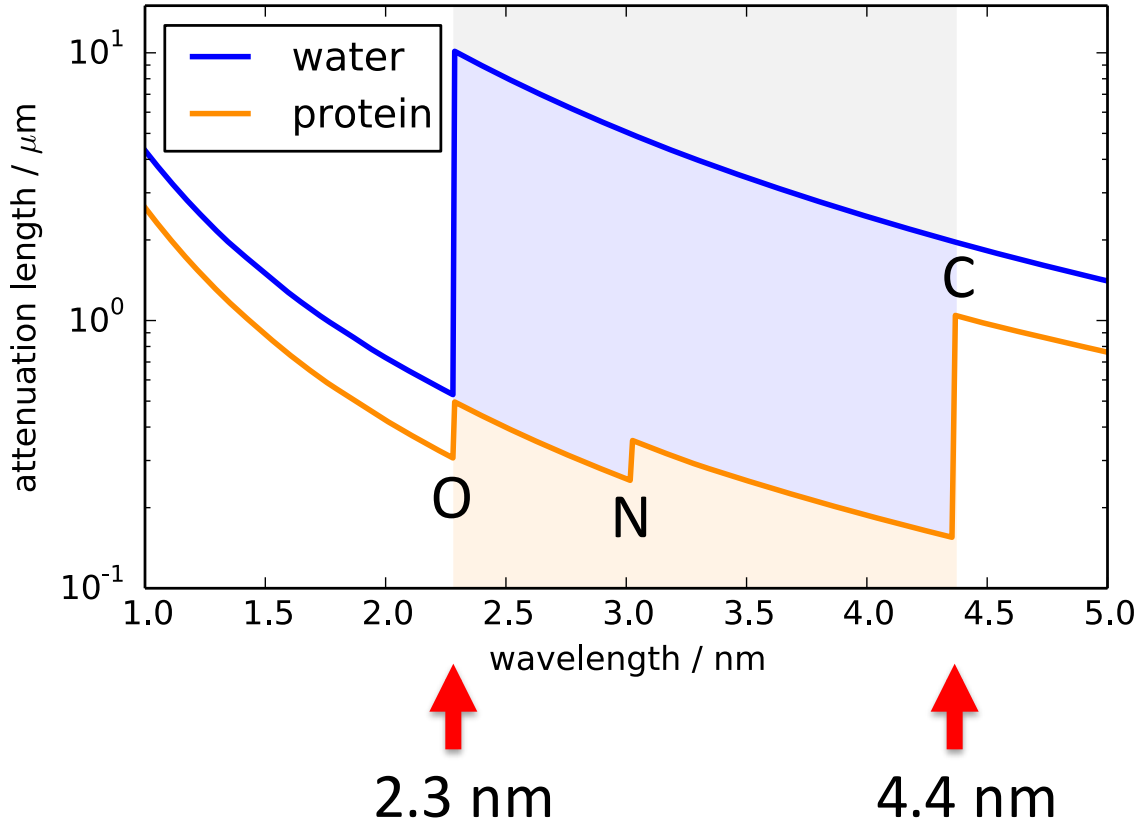
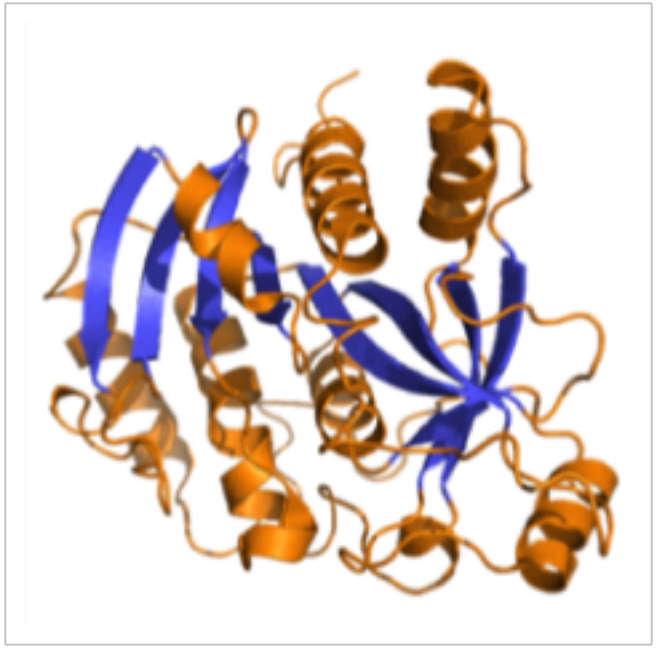
The Water Window

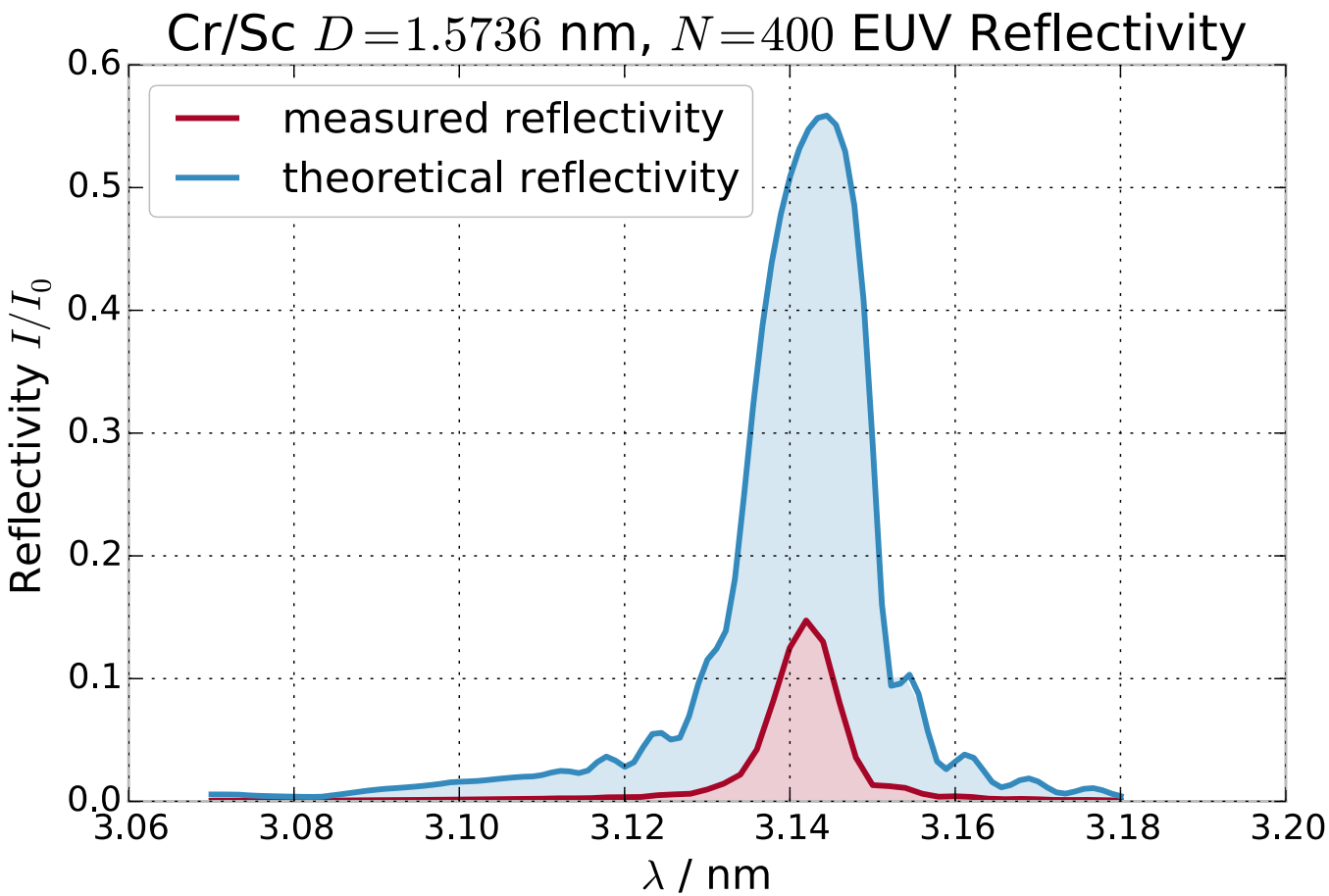


- AOI 1.5°
- Sc edge: 3.11 nm



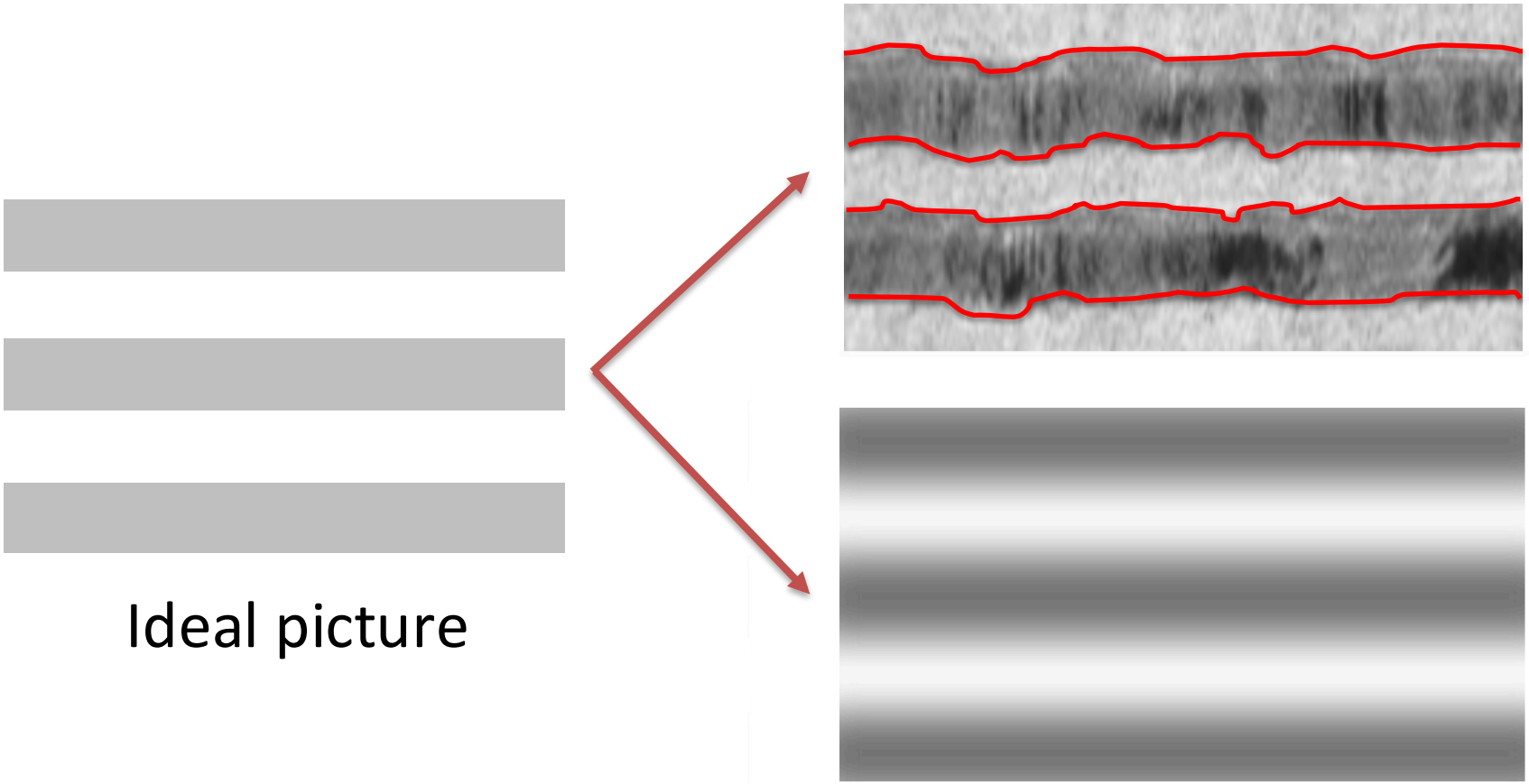
Problem: Limited Reflectivity

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



Interface Properties

Roughness (diffuse scattering)

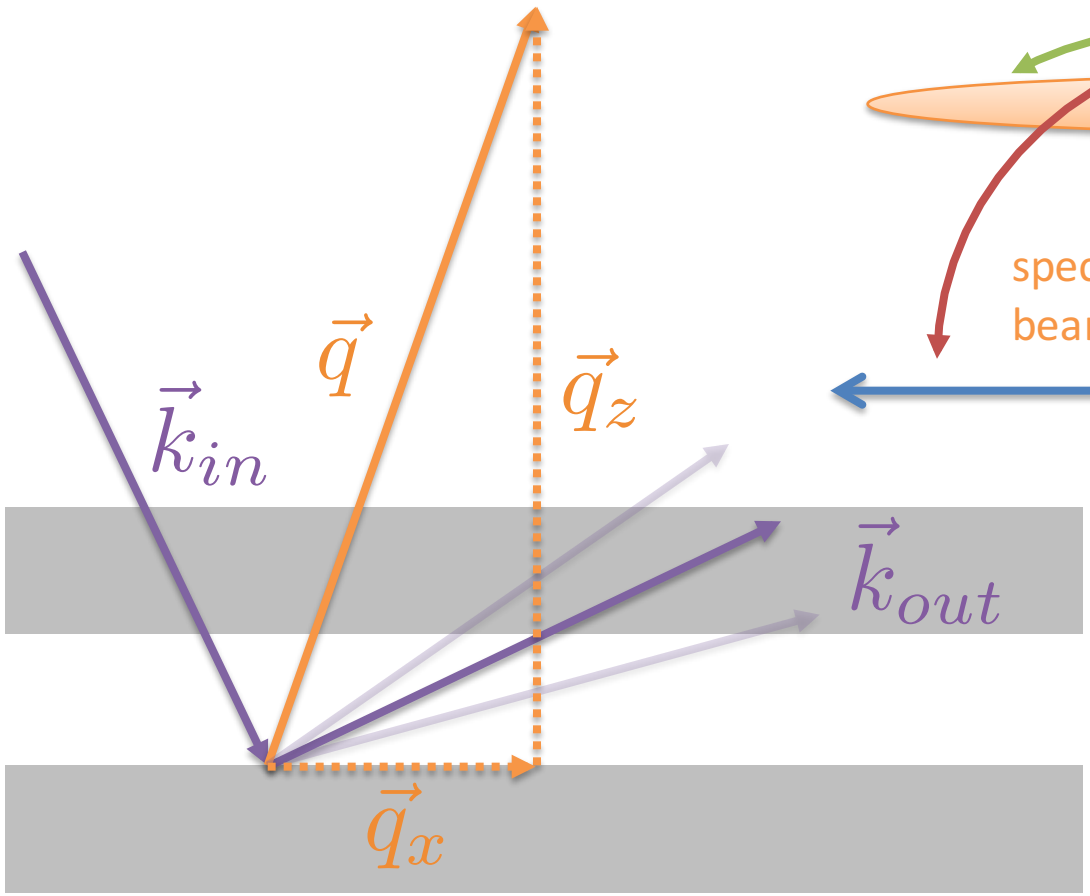


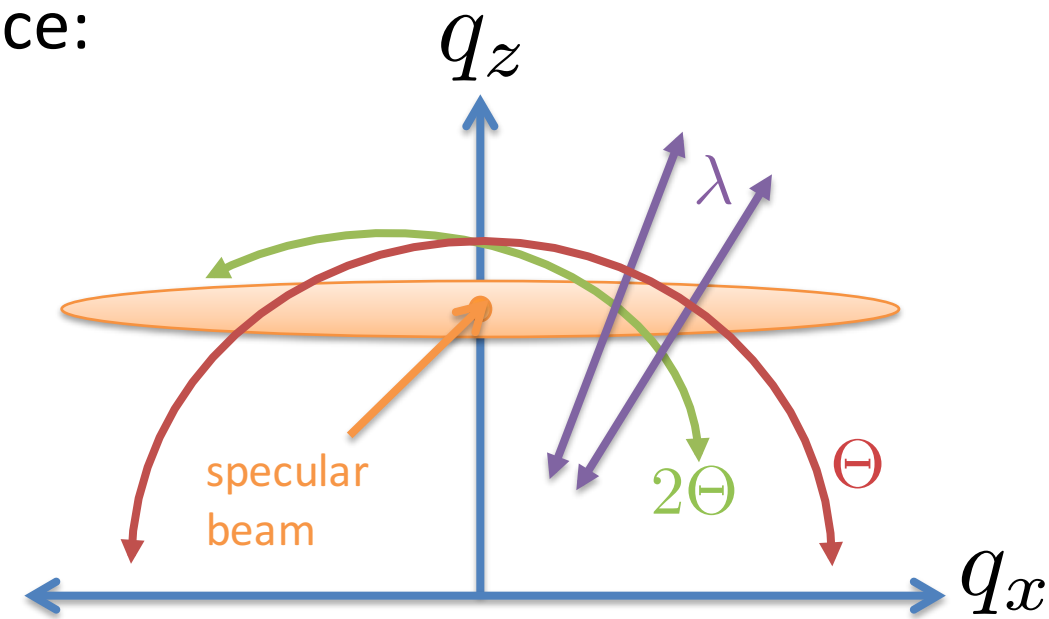
Ideal picture

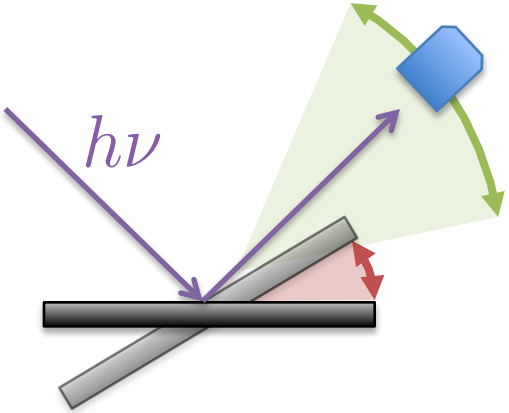
Interdiffusion
(diminished reflectivity)

Mapping Reciprocal Space

Typical angles of incidence:
1° – 7° from normal







DWBA Modelling

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{diffuse}} = \frac{A\pi^2}{\lambda^4}\sum_{j=1}^{N}\sum_{i=1}^{N}(n_j^2 - n_{j+1}^2)^*(n_i^2 - n_{i+1}^2)\Big((T_j^{(1)} + R_j^{(1)})^*(T_j^{(2)} + R_j^{(2)})^* \times (T_i^{(1)} + R_i^{(1)})(T_i^{(2)} + R_i^{(2)})\Big)c_\perp^{ij}(q_x)\, C(q_x)$$

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!

Haase et al.: Appl. Optics 53, No. 14, 3019-3027 (2014)

Roughness Model

$$C(q_x) = \frac{4\pi H \sigma^2 \xi_{\parallel}^2}{(1 + |q_x|^2 \xi_{\parallel}^2)^{1+H}}$$

H : Hurst factor, jaggedness of surface

σ : root mean square roughness

$\xi_{\parallel}$: lateral correlation length

Vertical Correlation Function:

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

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

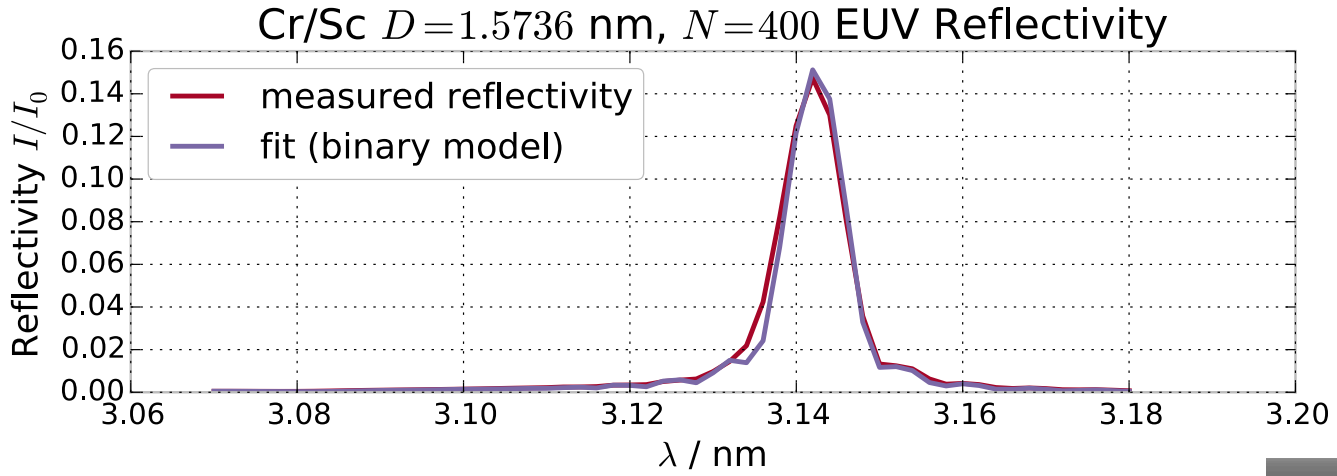
d_n :thickness of nth layer

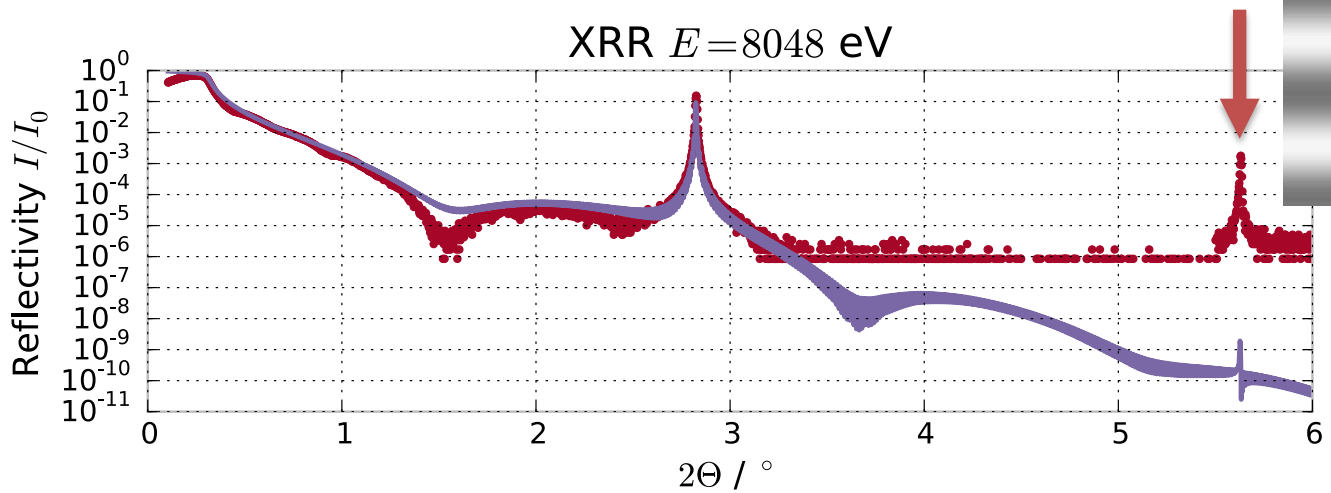
De Boer: Phys. Rev. B 51, 5297 (1994)

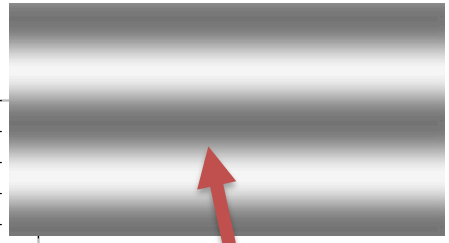
De Boer: Phys. Rev. B 53, 6048 (1995)

Spiller et al.: J. Appl. Phys. 74, 107-118 (1993)

Binary Layer Approach







Graded interface model needed!

Binary Model with only Nevot/Croce damping factor fails

Analysis Strategy

Parameters:

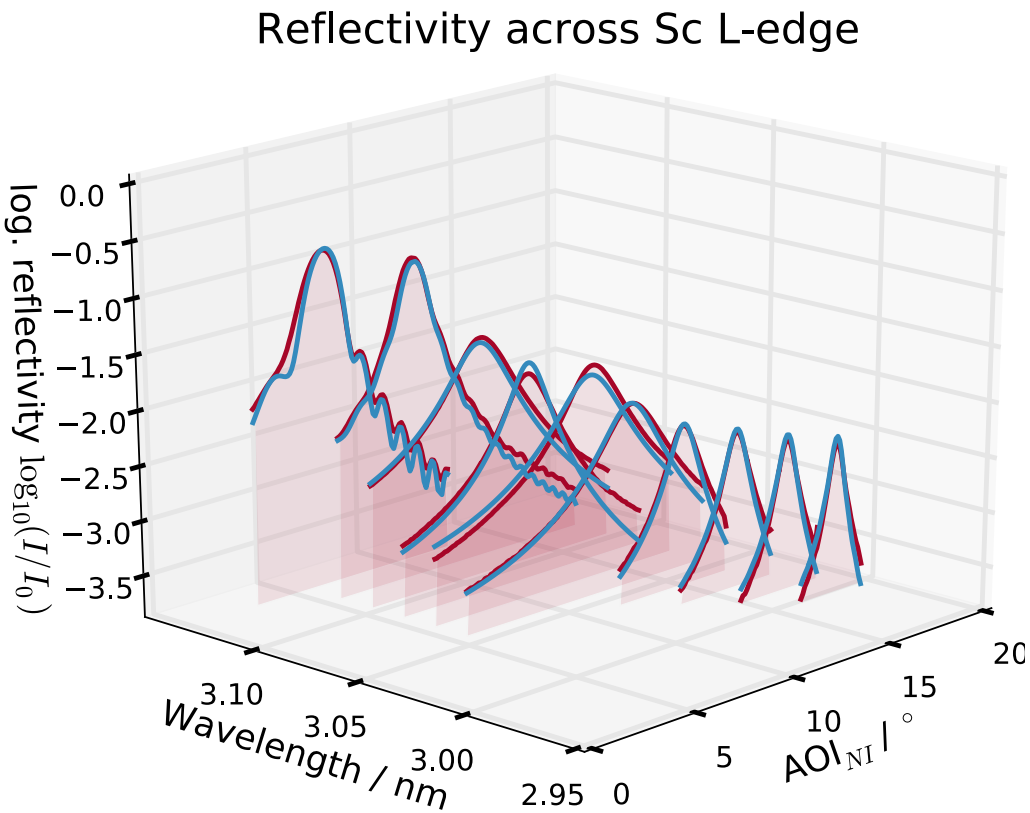
- Multilayer period *D*
- *Sc* and *Cr* layer thicknesses
- Interdiffusion/mixing of the two materials
- Interface properties/shape
- Nevot/Croce factor (roughness)

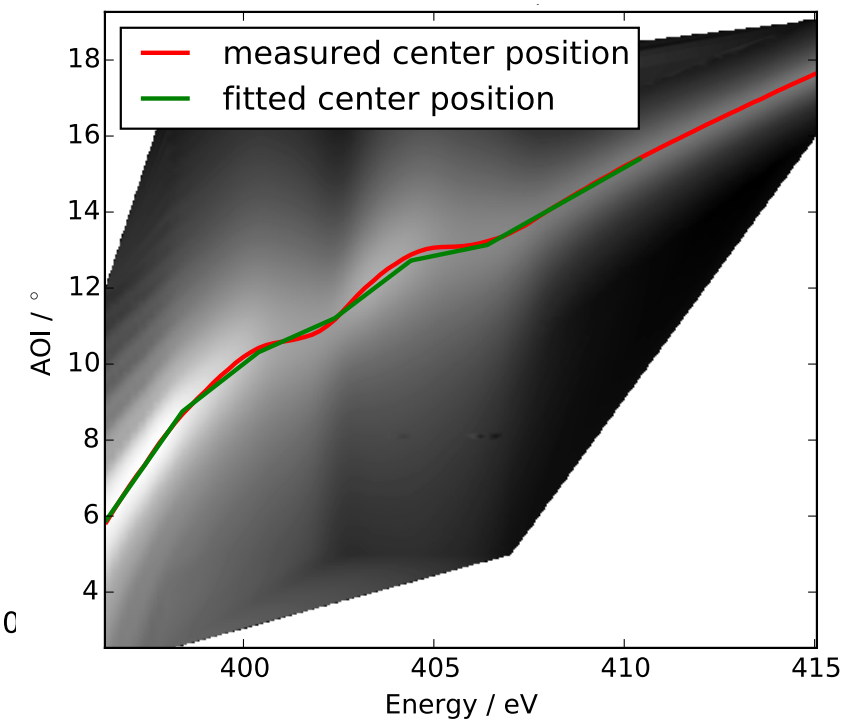
Combination of complementary methods:

- 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

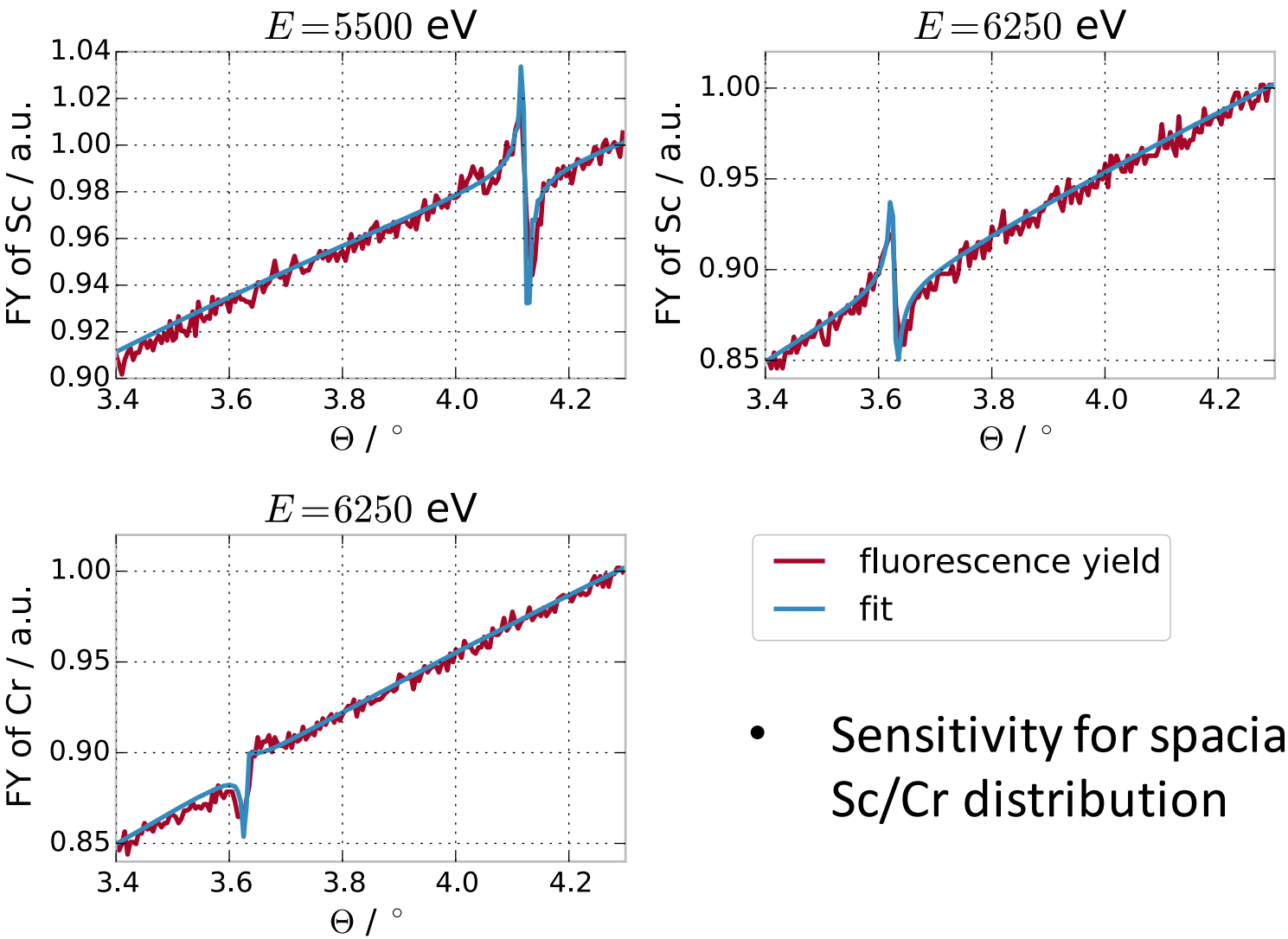
Resonant EUV Reflectivity





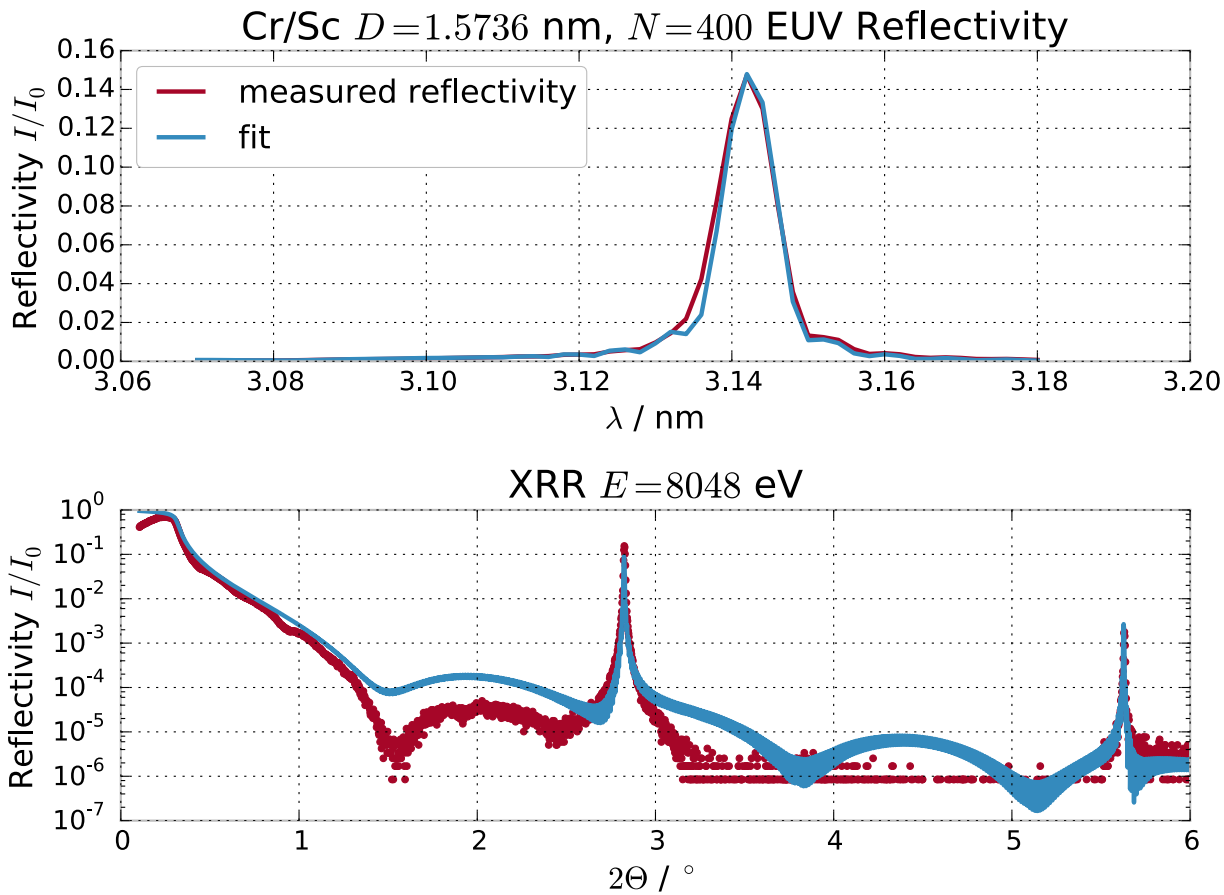
- Sensitivity for Sc content and total layer thickness D
- 50 % Sc, 50 % Cr

X-ray Standing Wave



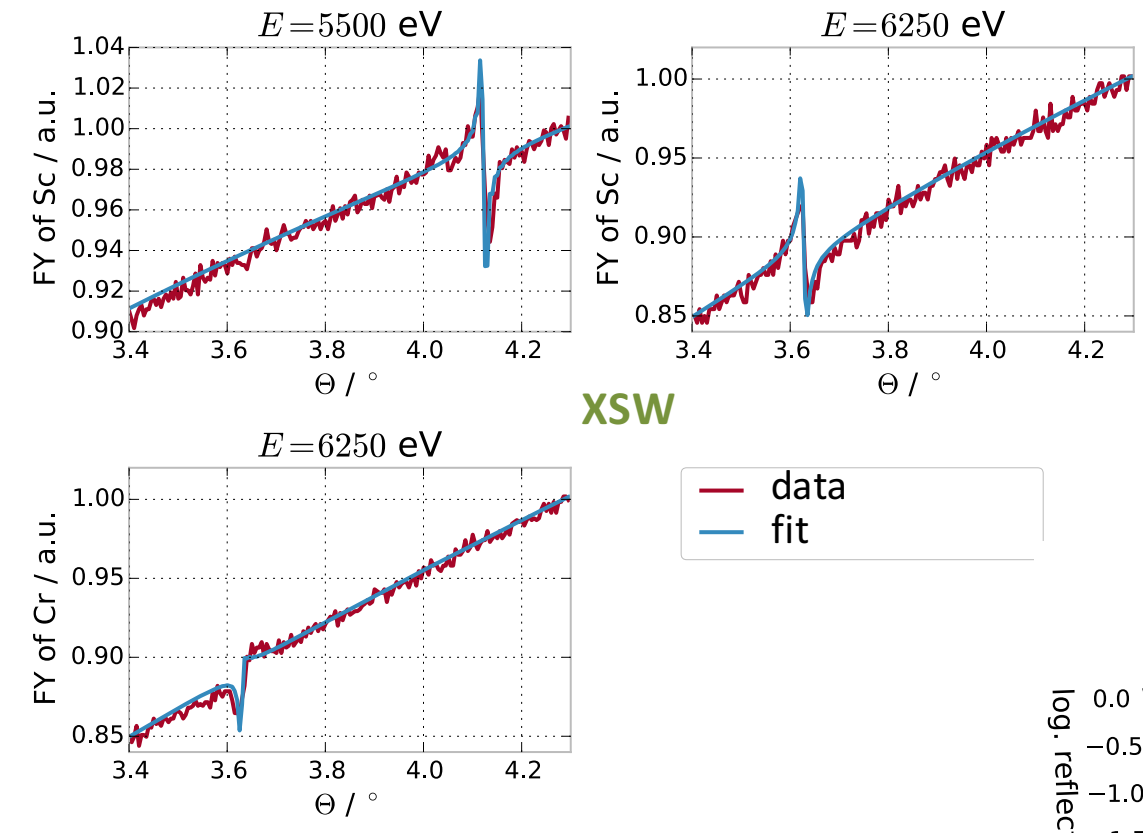
- Sensitivity for spacial Sc/Cr distribution

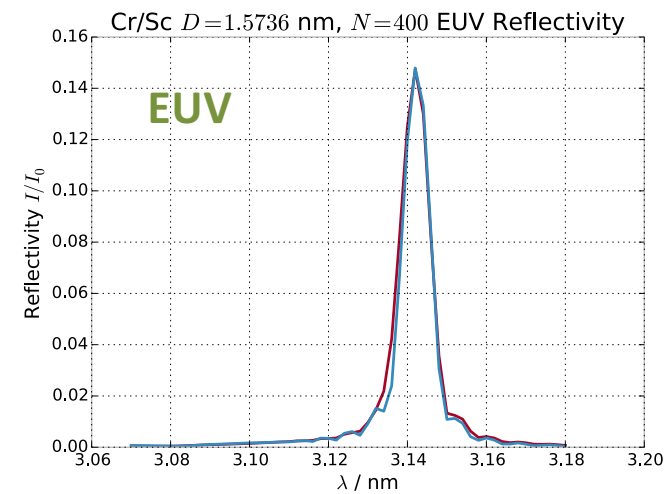
EUV and X-ray Reflectivity

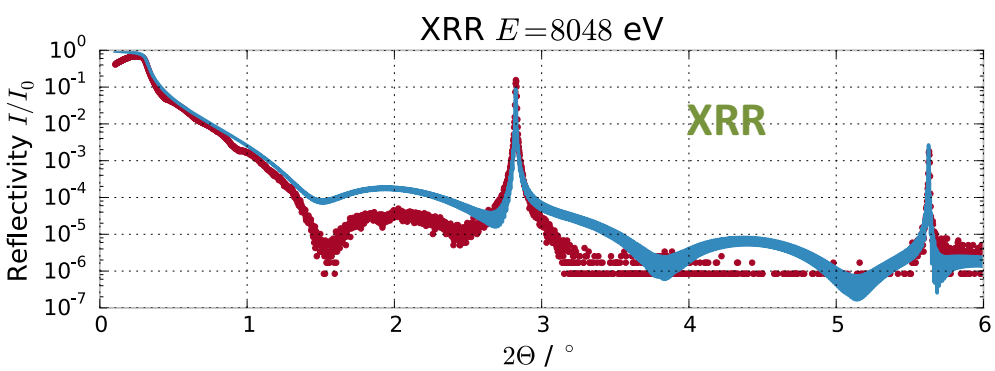


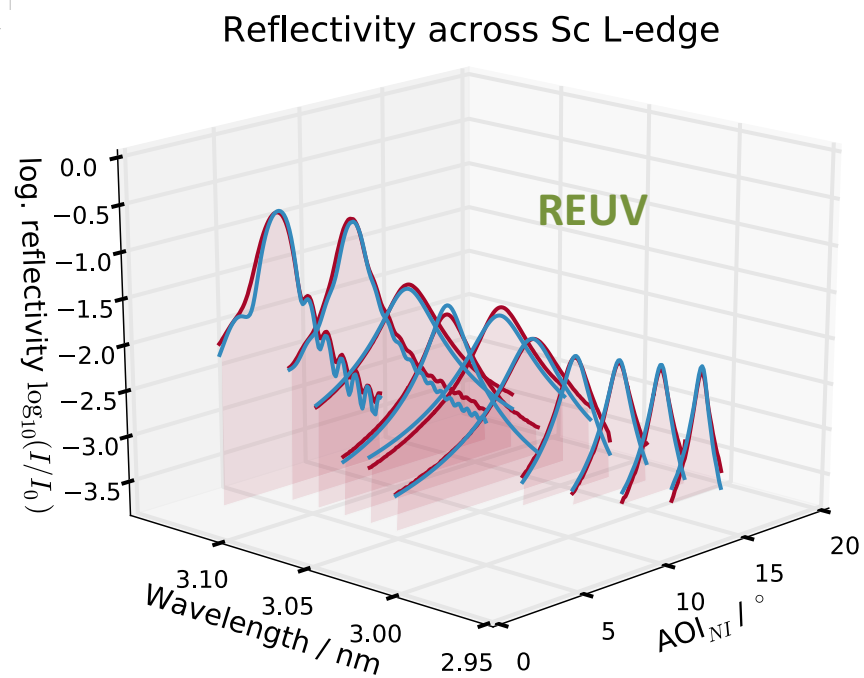
- Sensitivity for total layer thickness D and interface asymmetry

Combined Fit

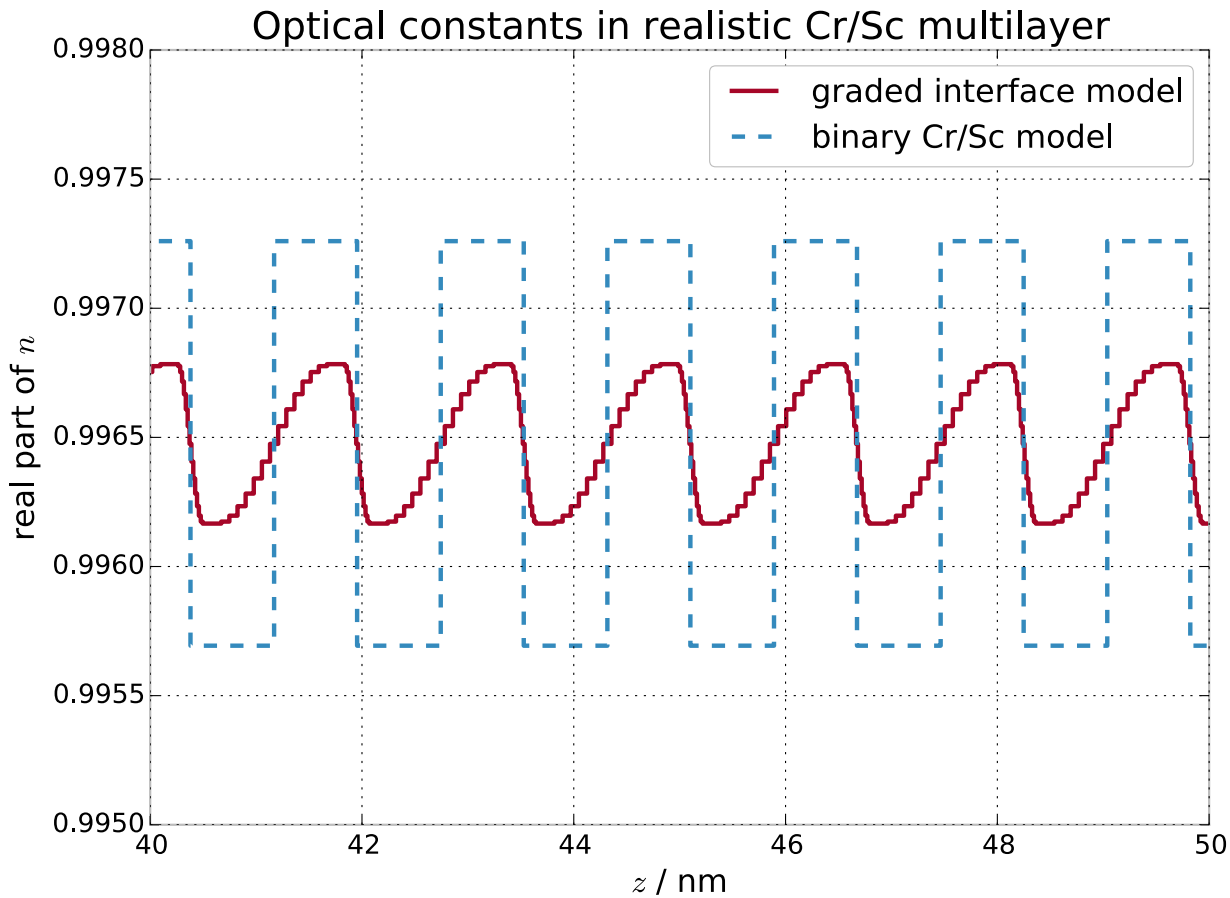








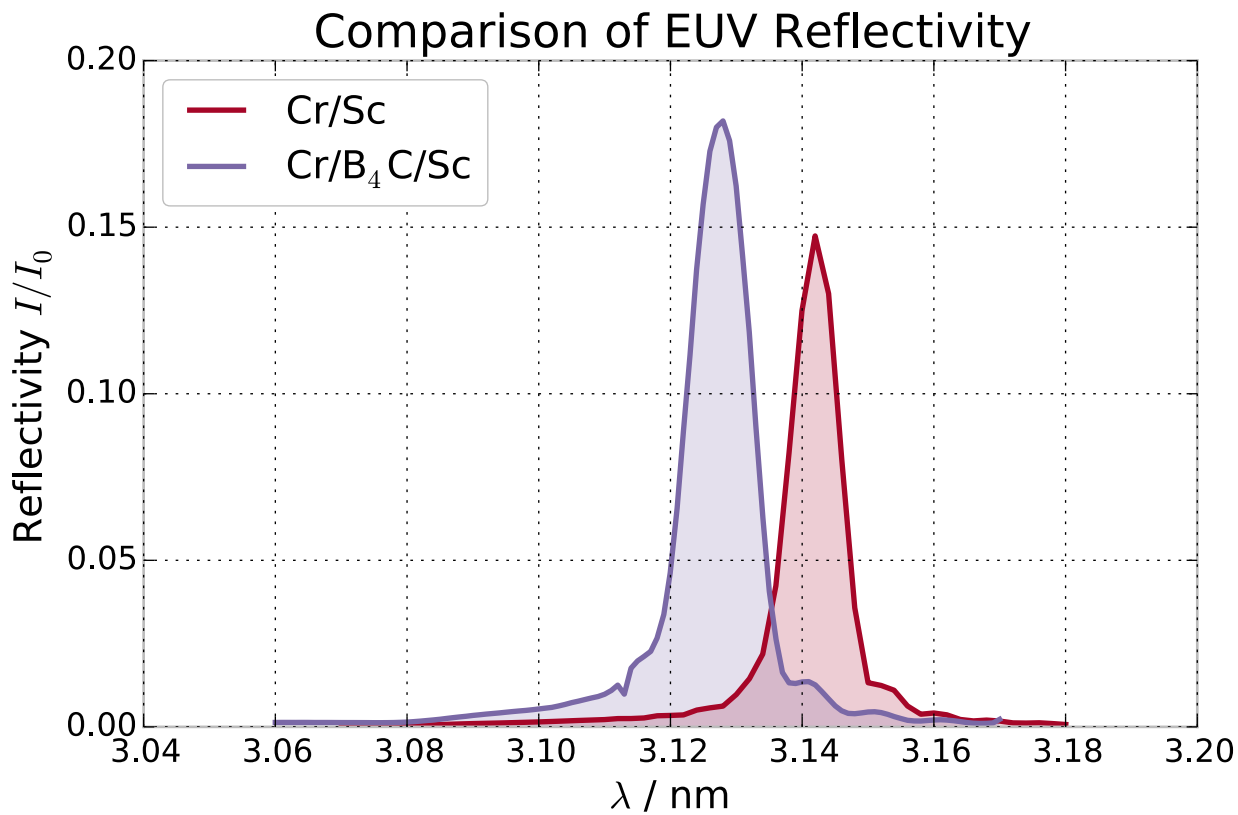
Consistent Model



- The two layers interdiffuse strongly (60 %)
- Asymmetric interface gradients
- “Undisturbed system” for DWBA analysis

B_4C 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)

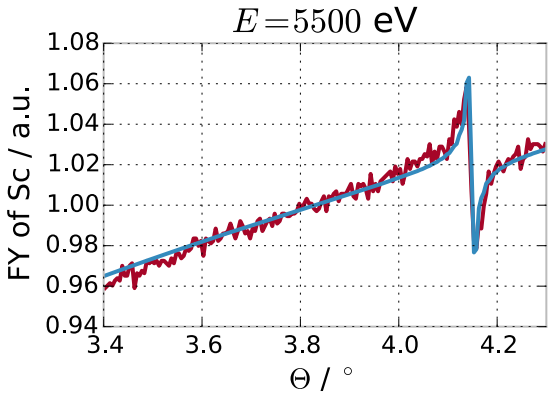


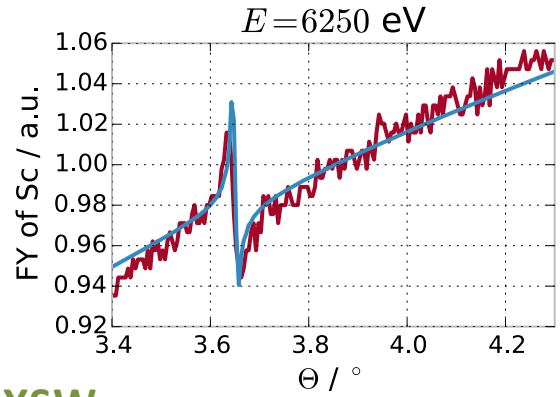
Treat as effective two layer system:

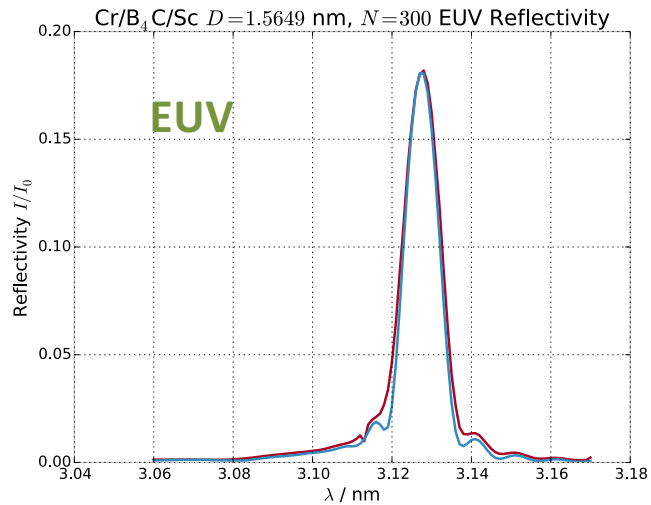
$w*n_C + (1-w)*n_{Sc}$

$w*n_B + (1-w)*n_{Cr}$

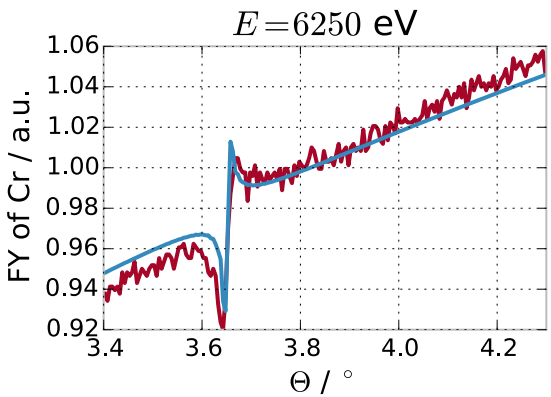
Combined Fit



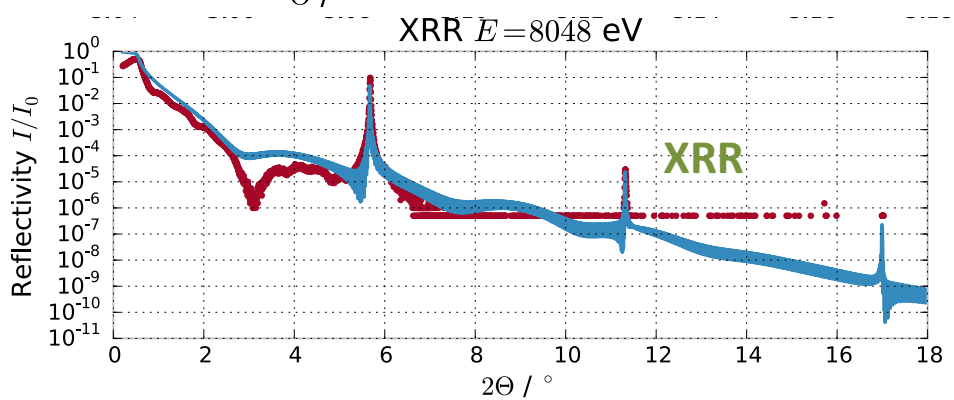




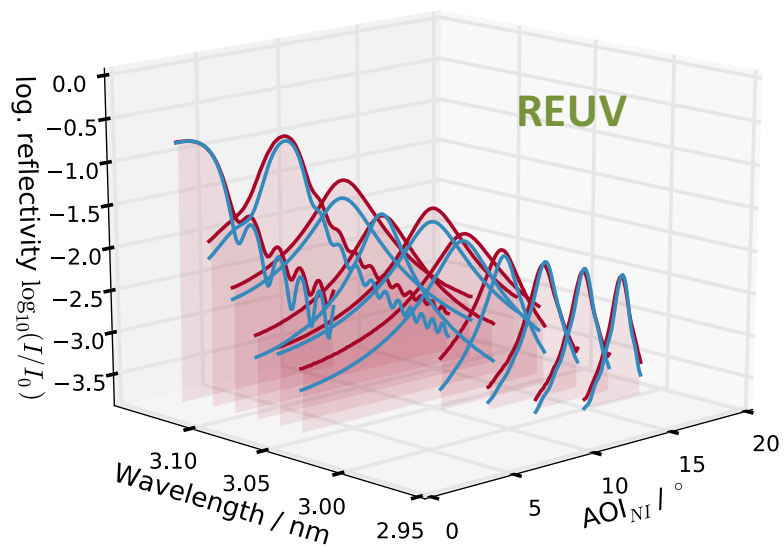
XSW



data
fit

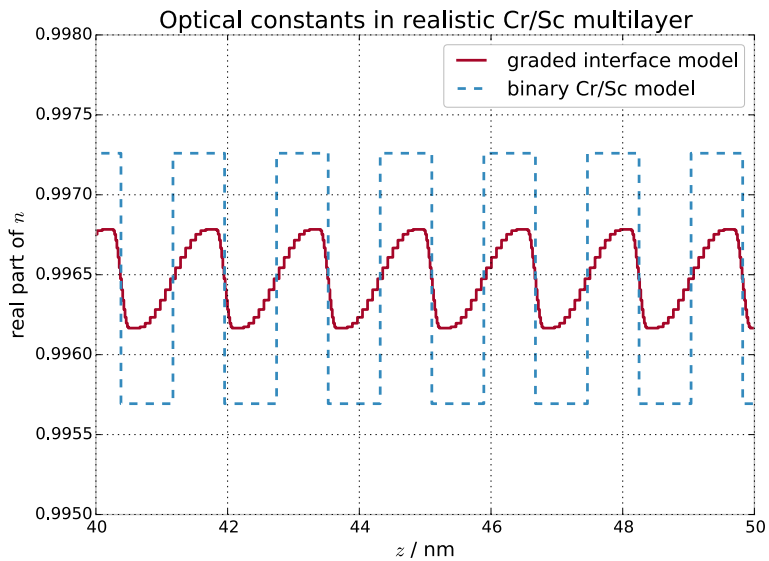


Reflectivity across Sc L-edge

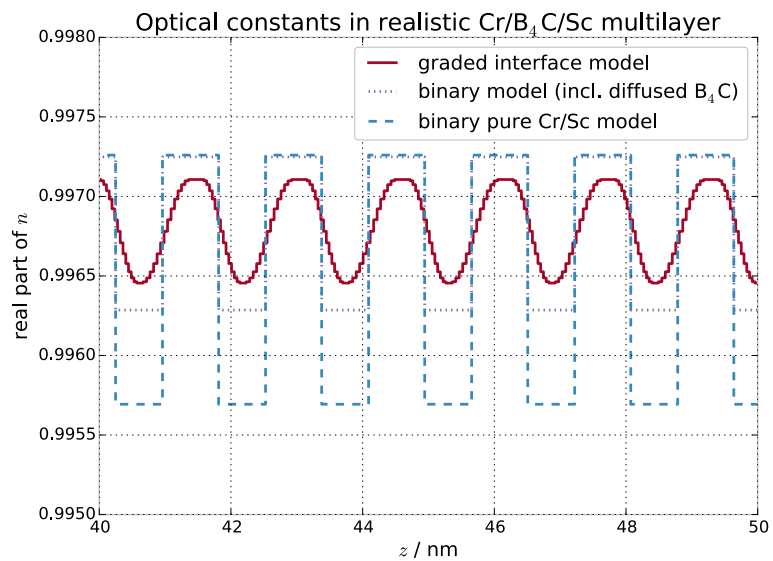


Results in Comparison

Cr/Sc

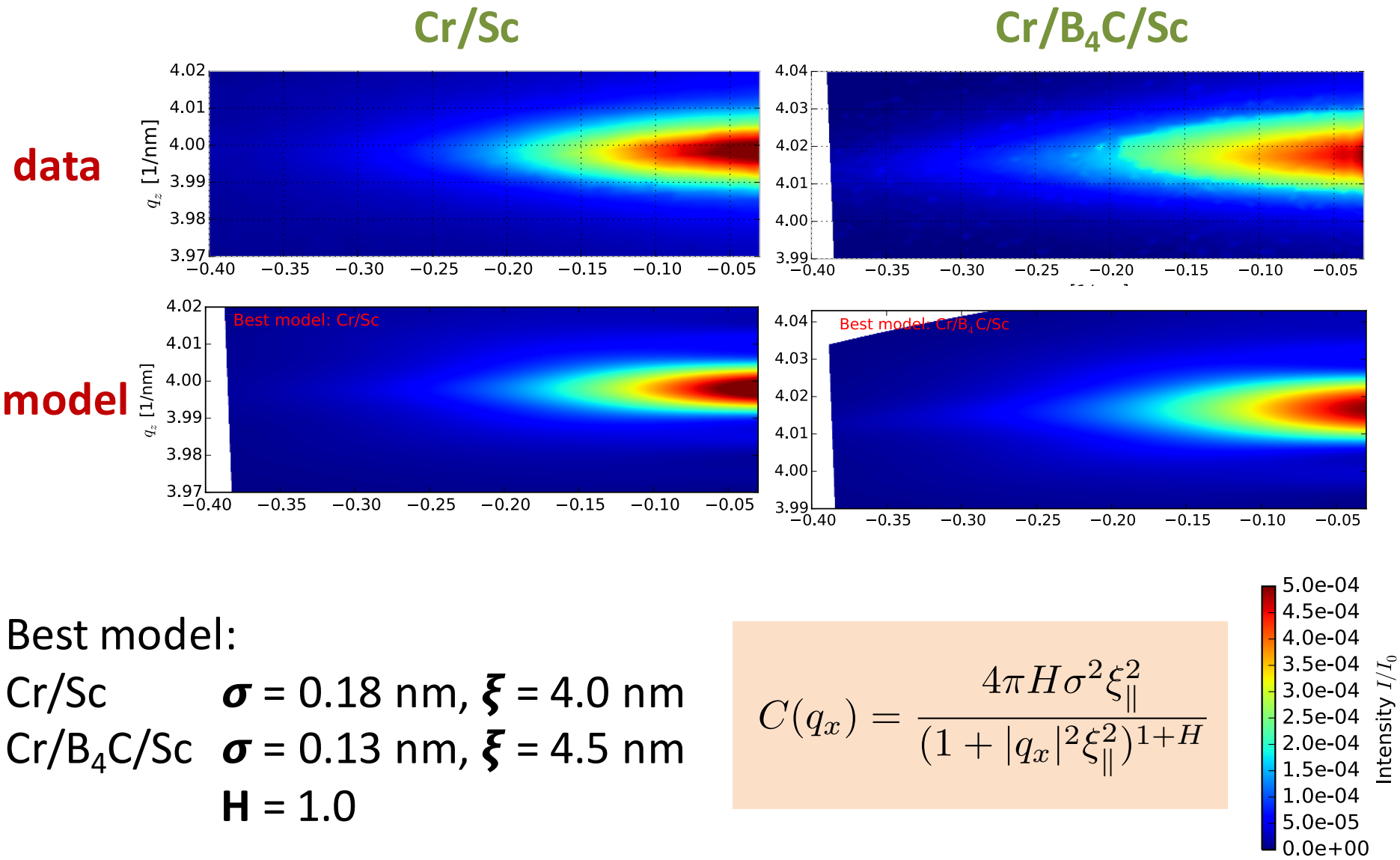


$Cr/B_4C/Sc$



- Similar interdiffusion is observed for both systems
- Interface profiles are less asymmetric with B_4C

Diffuse Scattering



Best model:

Cr/Sc $\boldsymbol{\sigma}$ = 0.18 nm, $\boldsymbol{\xi}$ = 4.0 nm

Cr/B_4C/Sc $\boldsymbol{\sigma}$ = 0.13 nm, $\boldsymbol{\xi}$ = 4.5 nm

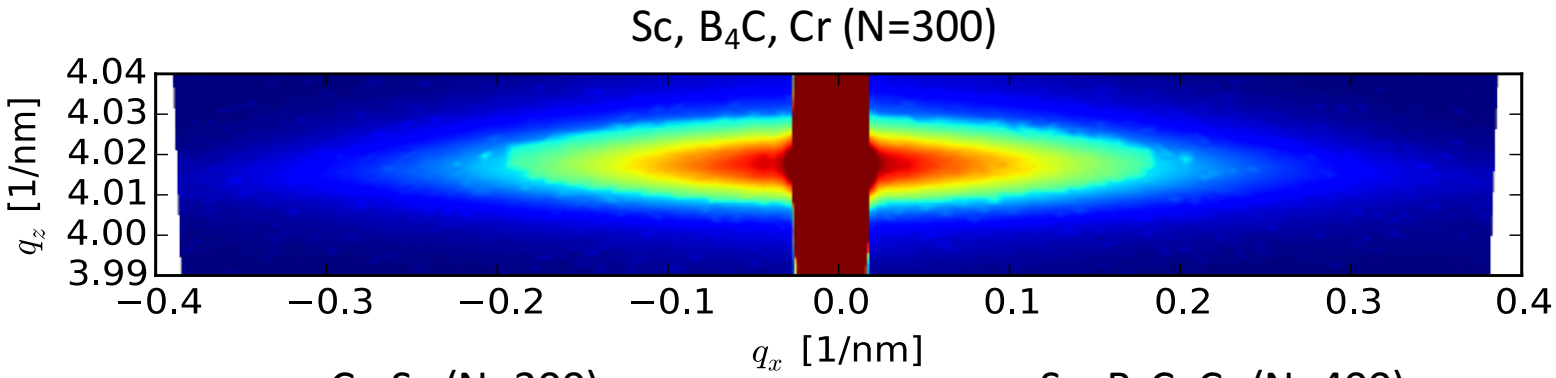
H = 1.0

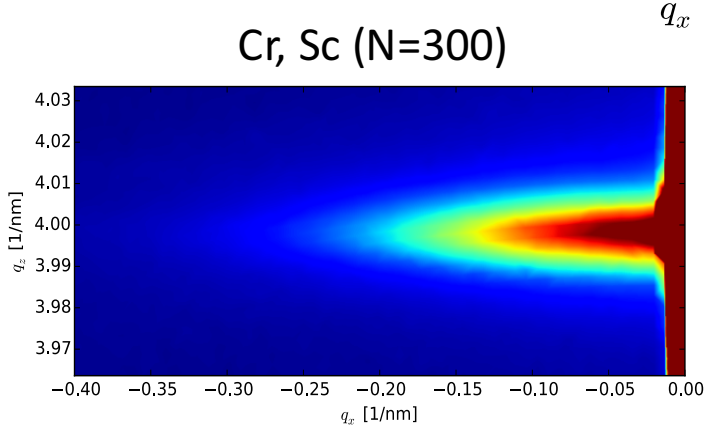
$$C(q_x) = \frac{4\pi H \sigma^2 \xi_{\parallel}^2}{(1 + |q_x|^2 \xi_{\parallel}^2)^{1+H}}$$

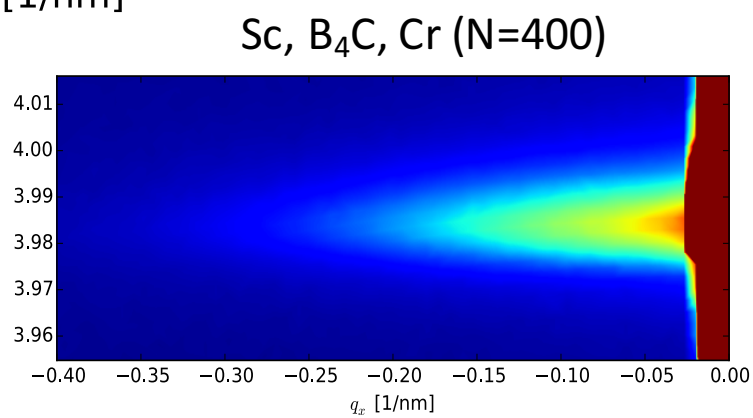
Summary and Outlook

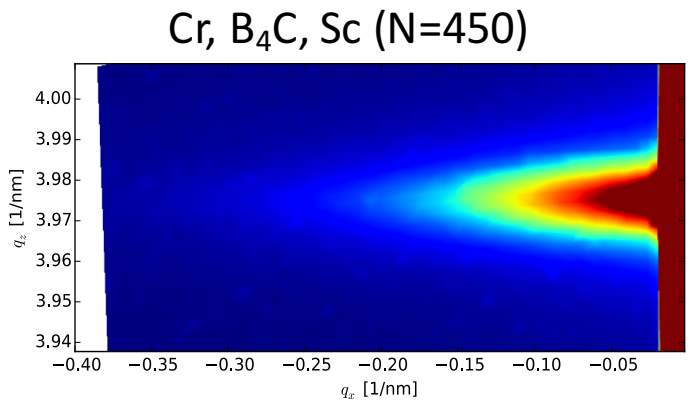
- The combination of several complementary methods are required to deduct a reliable model
- Ultra-thin multilayer systems require explicit modeling of the interfaces showing strong interdiffusion
- Effective power spectral density (roughness) can be extracted by DWBA simulations based on the explicit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

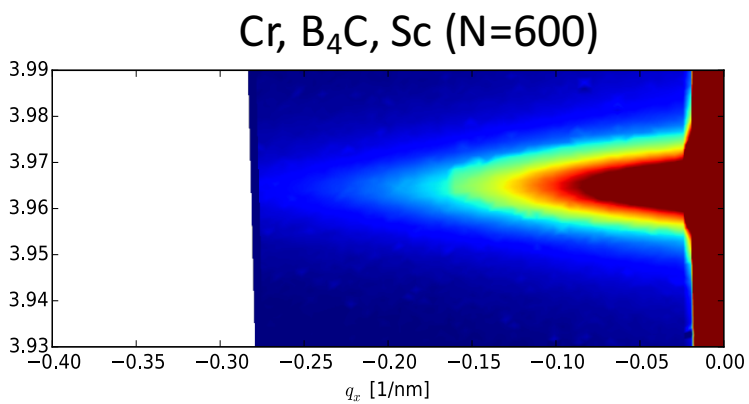
Diffuse Scattering Maps





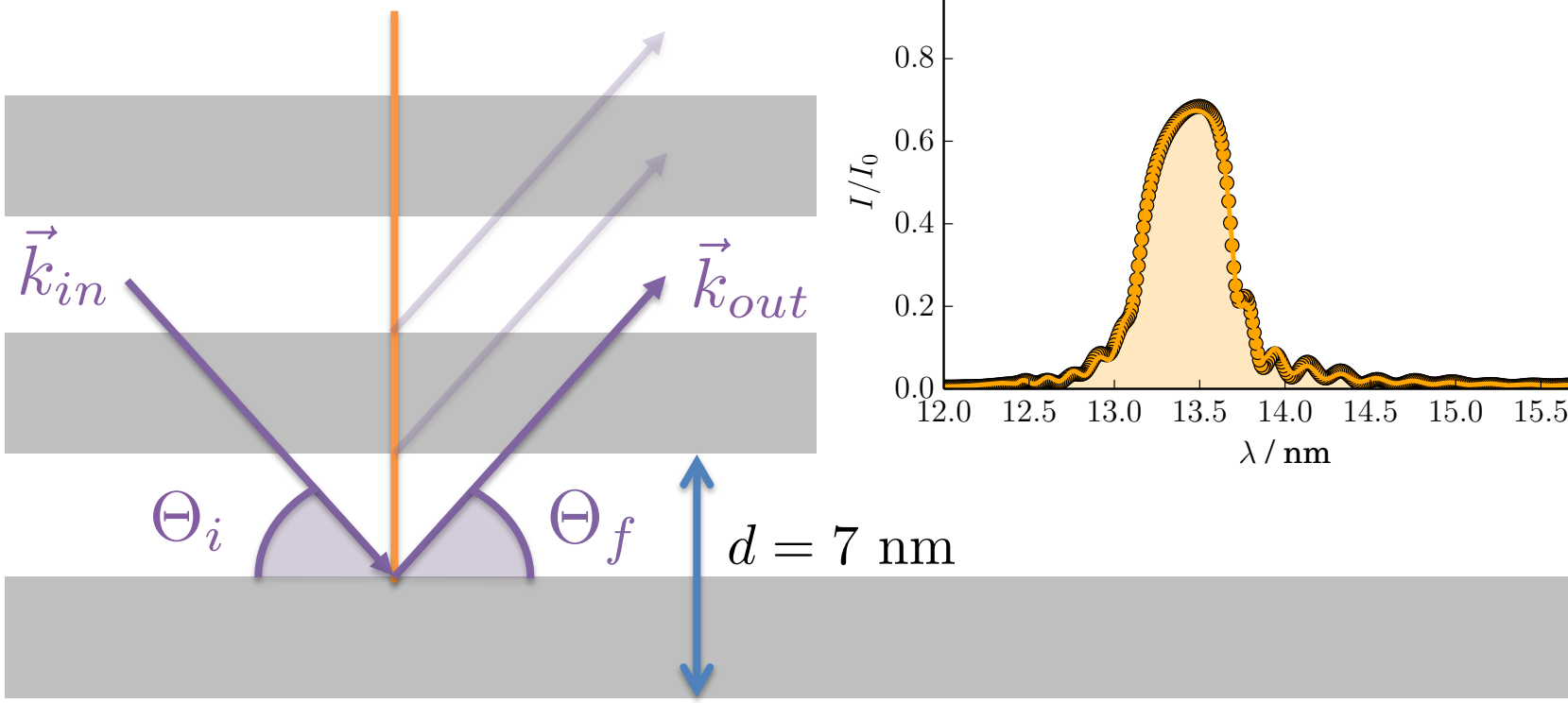


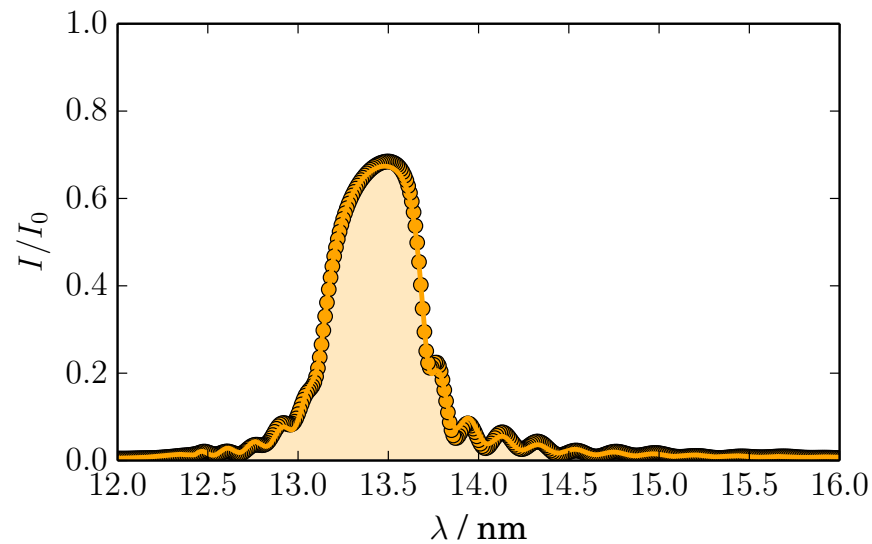




Multilayer Mirror Principle

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



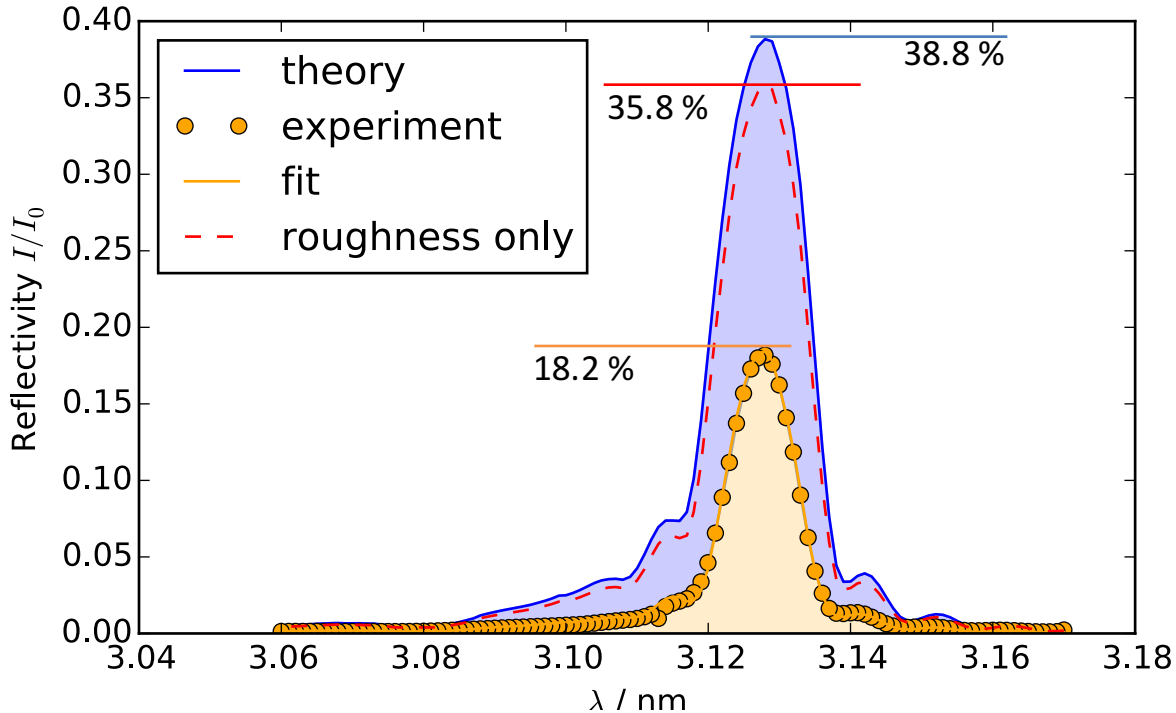


Roughness vs. Diffusion

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

σ_D: mean diffusion/roughness

σ_R: mean roughness only

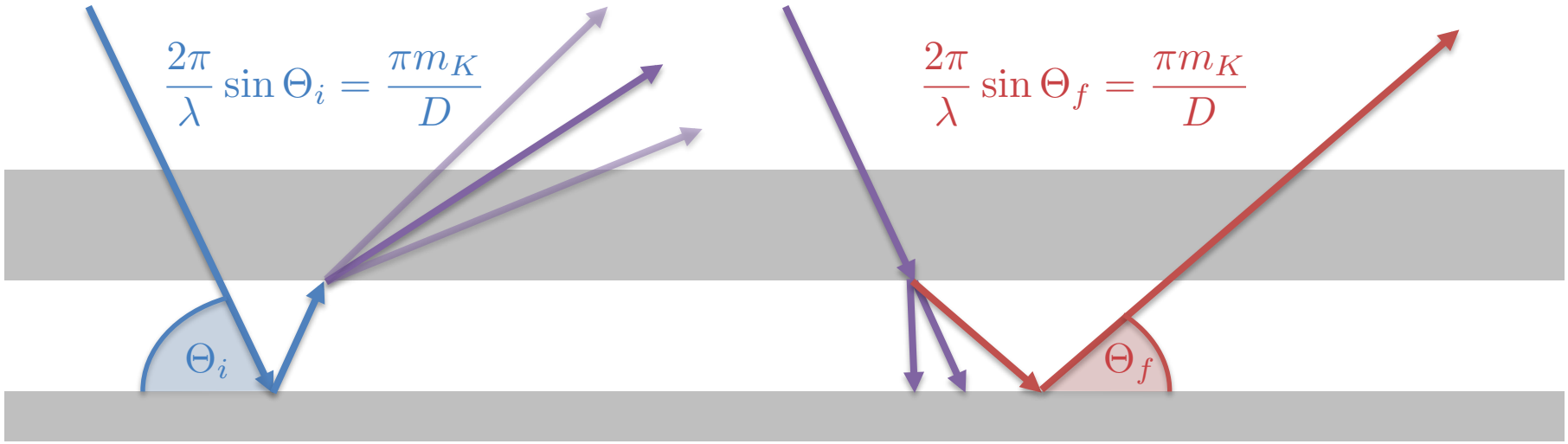


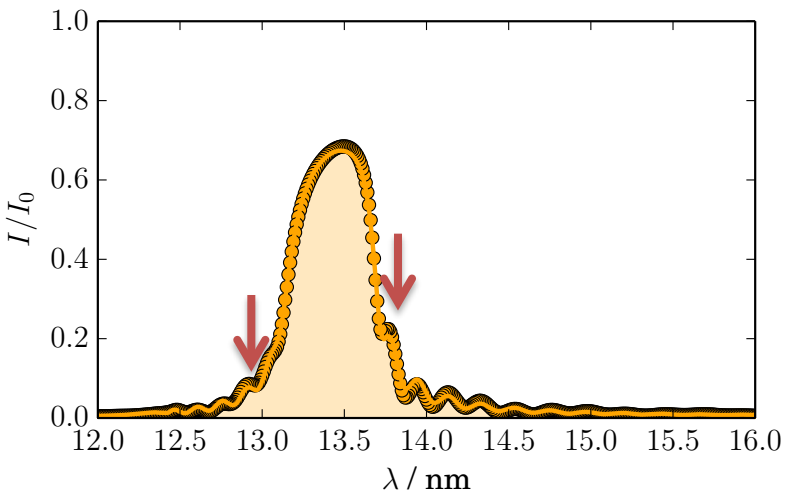
$$\sigma_D = 0.274 \text{ nm}$$

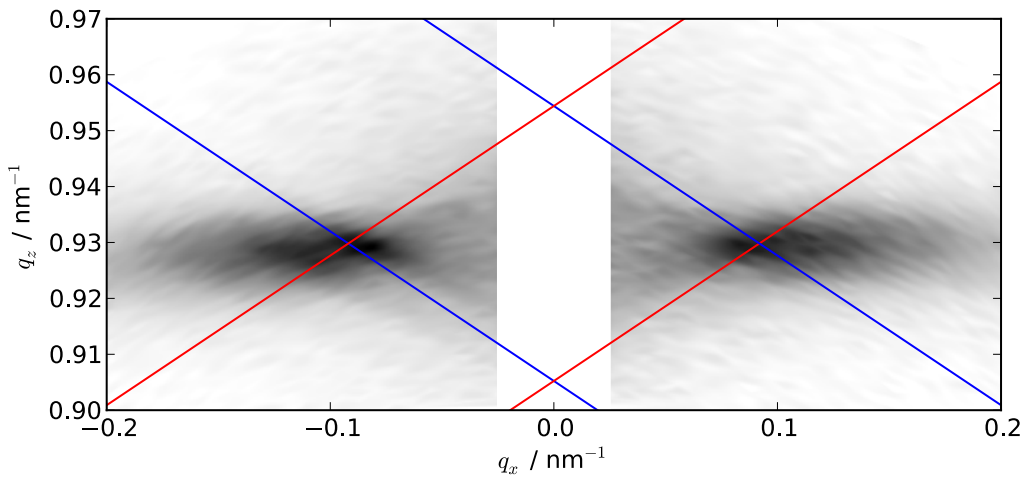
$$\sigma_R = 0.101 \text{ nm}$$

In contrast to $Mo/B_4C/Si$ multilayers, roughness is not the primary cause for reflectivity loss

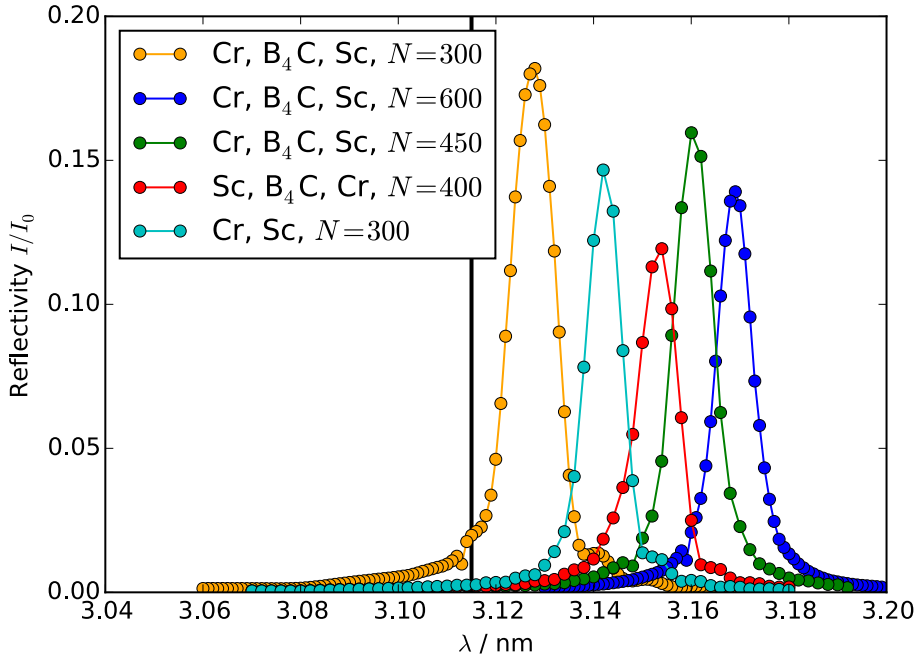
Dynamic Resonances





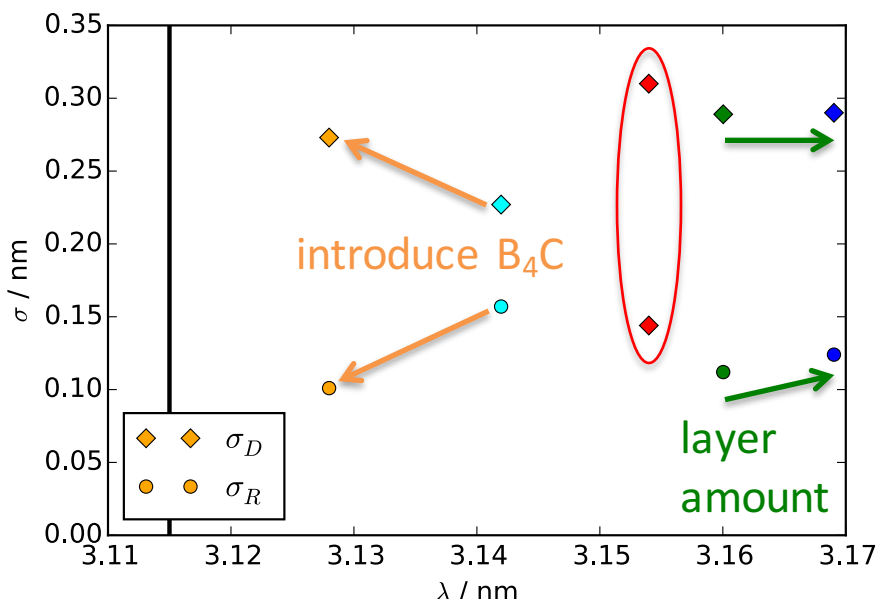


Diffusion Barrier B_4C

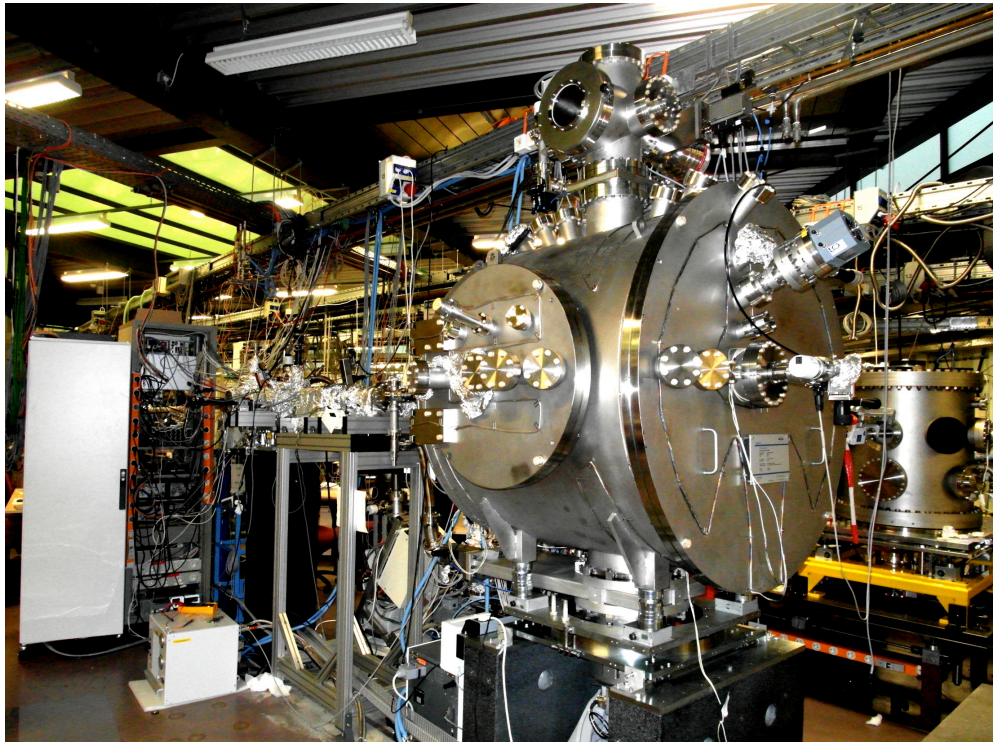


- All samples show similarly high roughness correlation laterally and vertically

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



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