Multiparameter Characterization of sub-nanometer Cr/Sc-Multilayers

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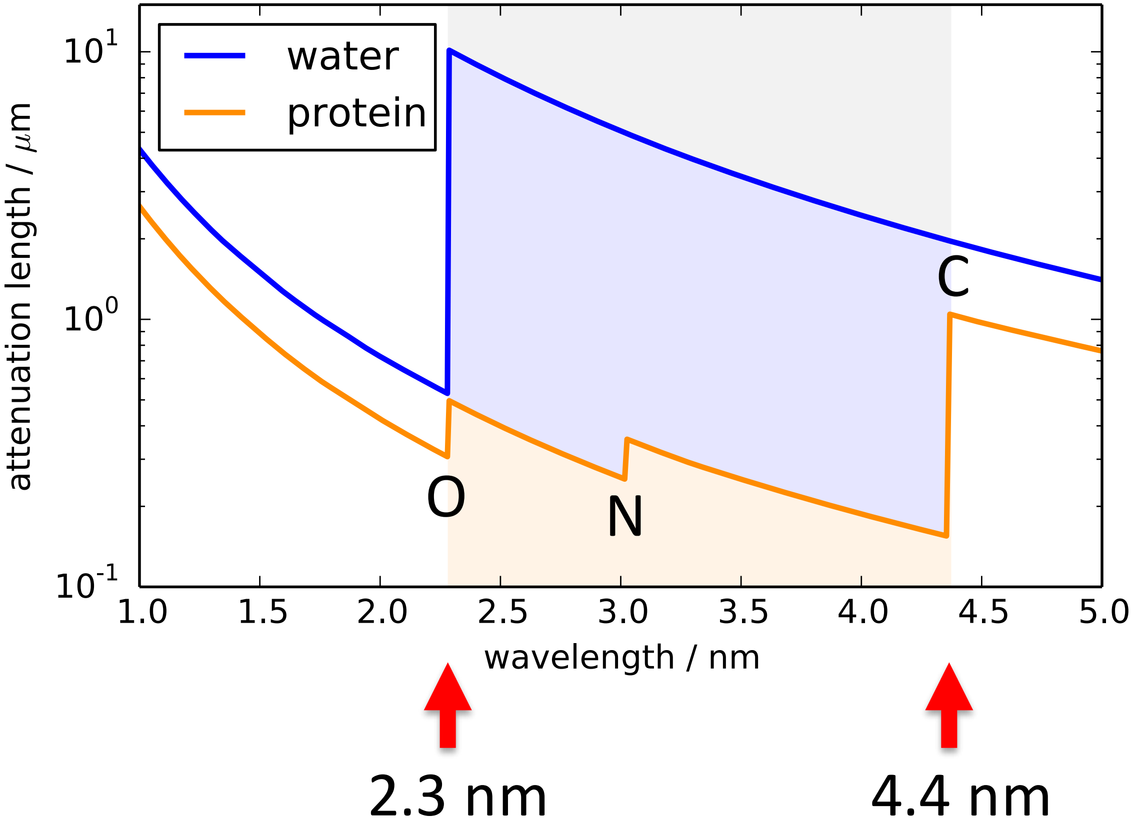
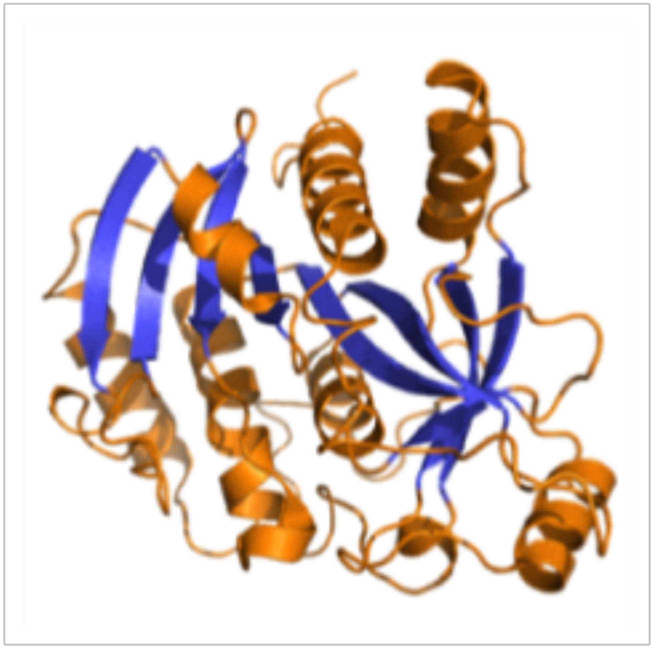
The Water Window

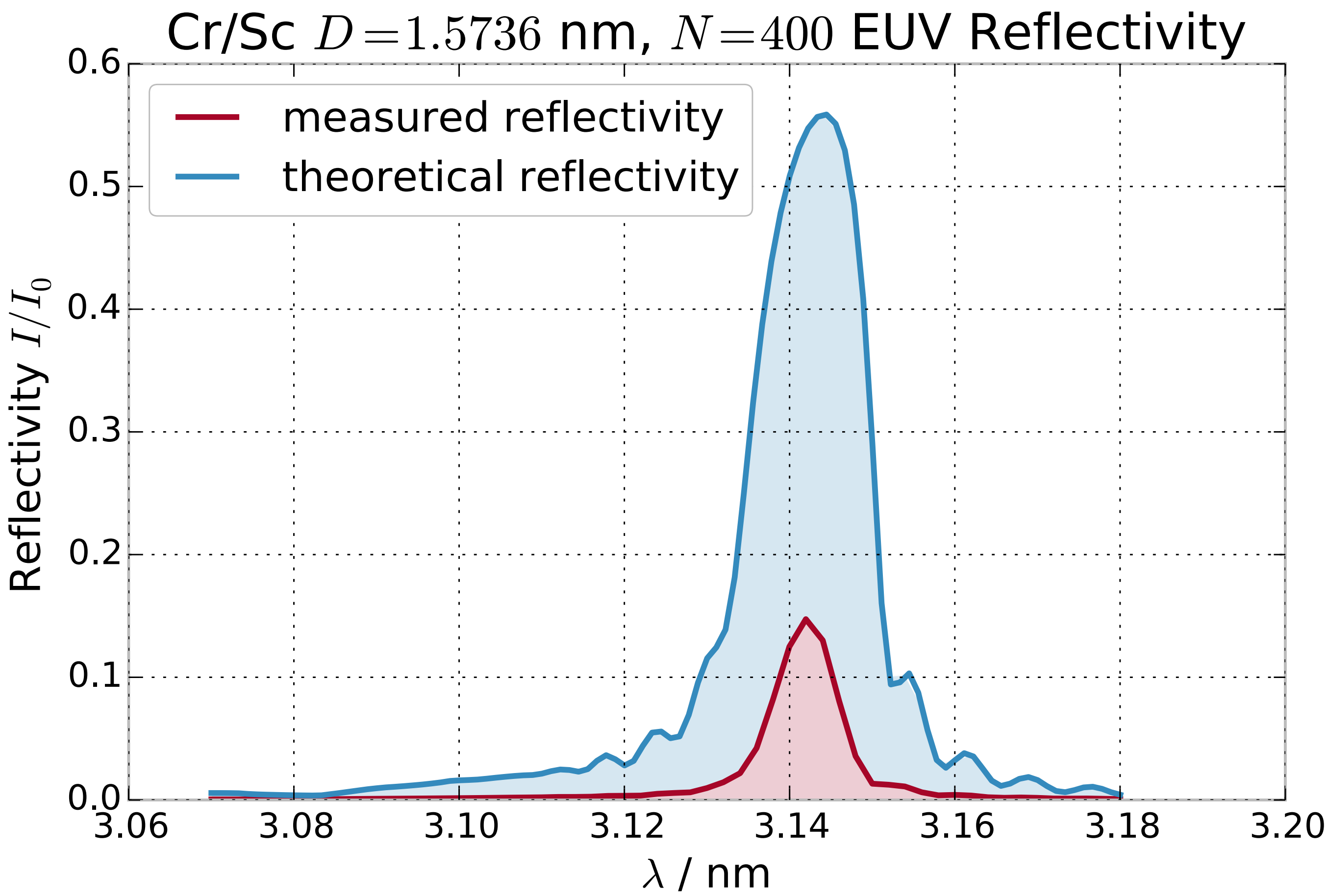


- AOI 1.5°
- Sc edge: 3.11 nm



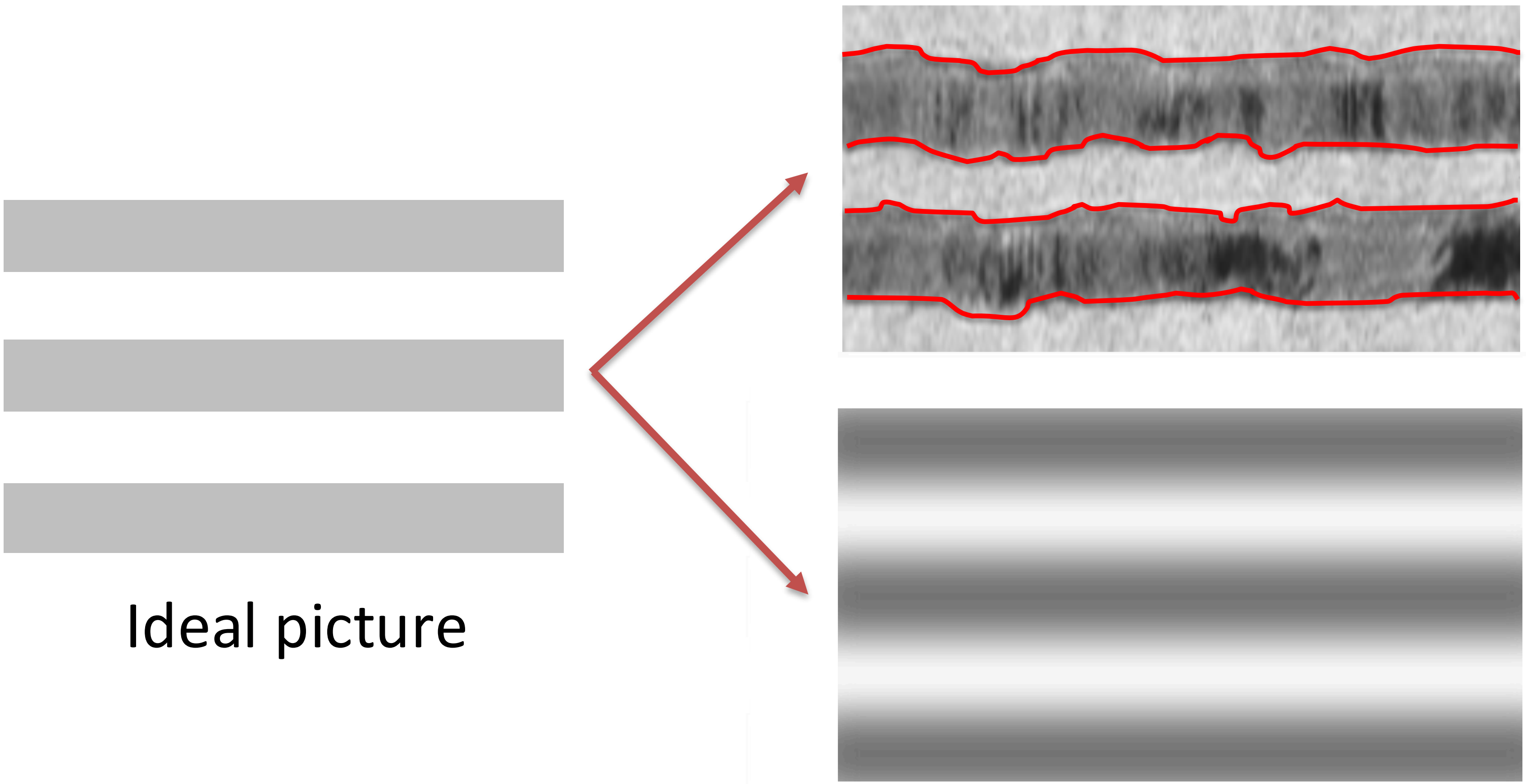
Problem: Limited Reflectivity

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



Interface Properties

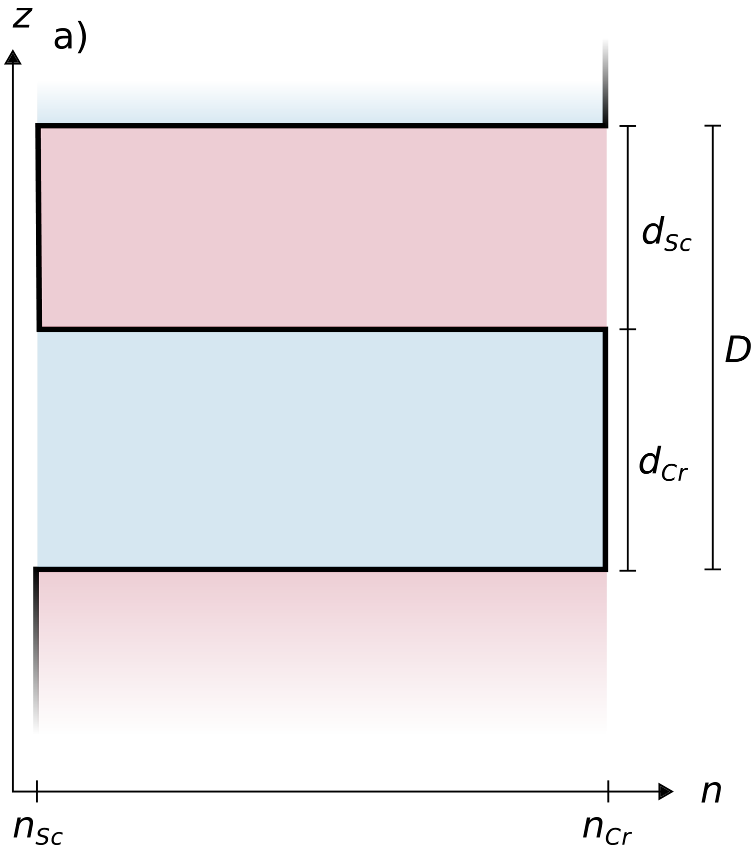
Roughness (diffuse scattering)



Ideal picture

Interdiffusion
(diminished reflectivity)

Binary Model

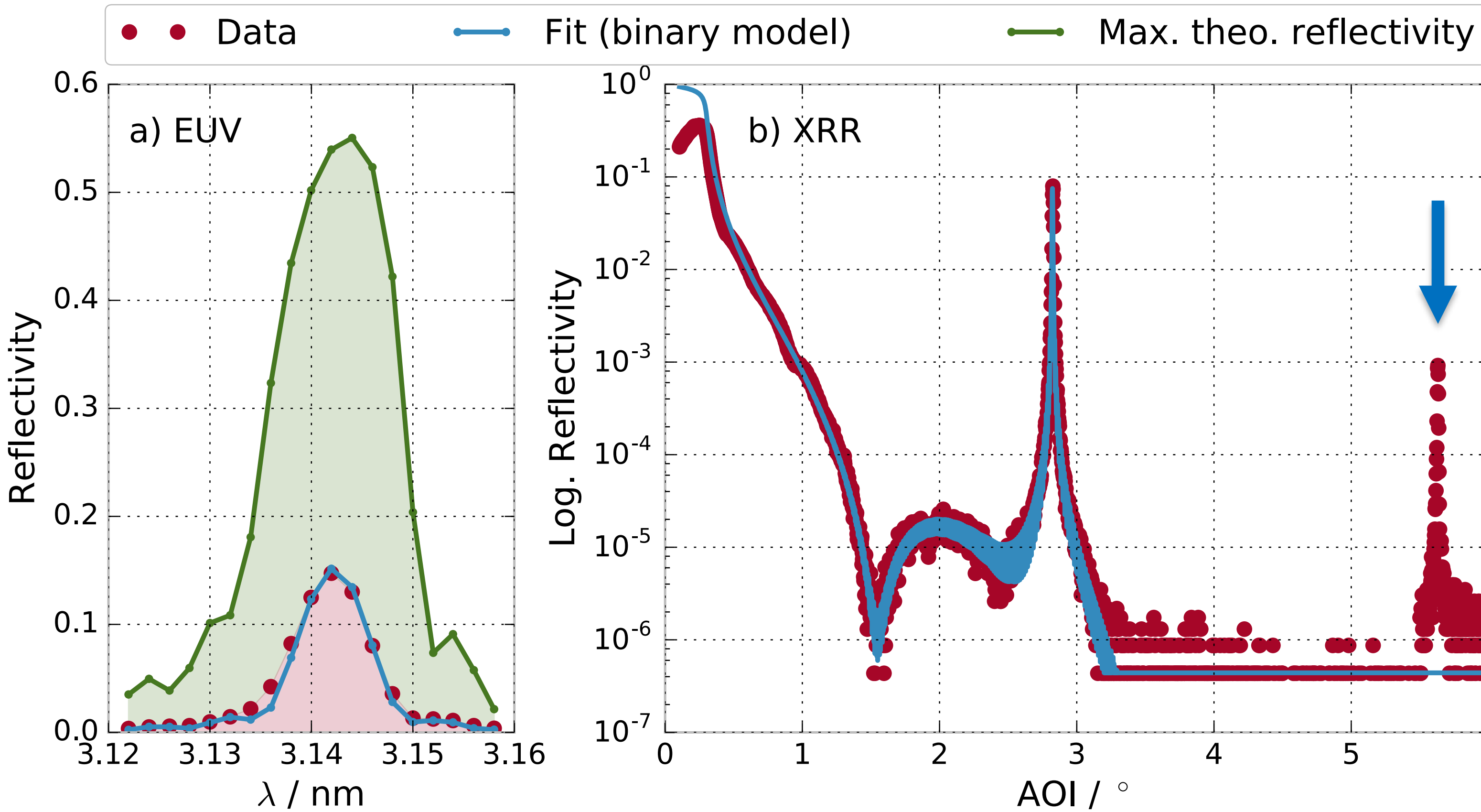


Parameters:

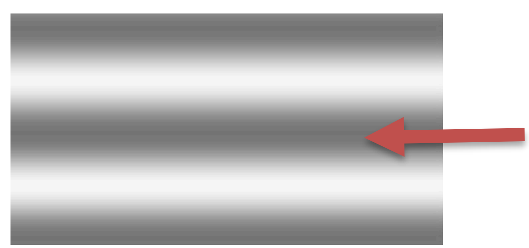
- Multilayer period *D*
- *Sc* and *Cr* layer thicknesses
- Nevot/Croce factor (roughness and interdiffusion)

Can the experiment be described with this model?

Binary Layer Approach

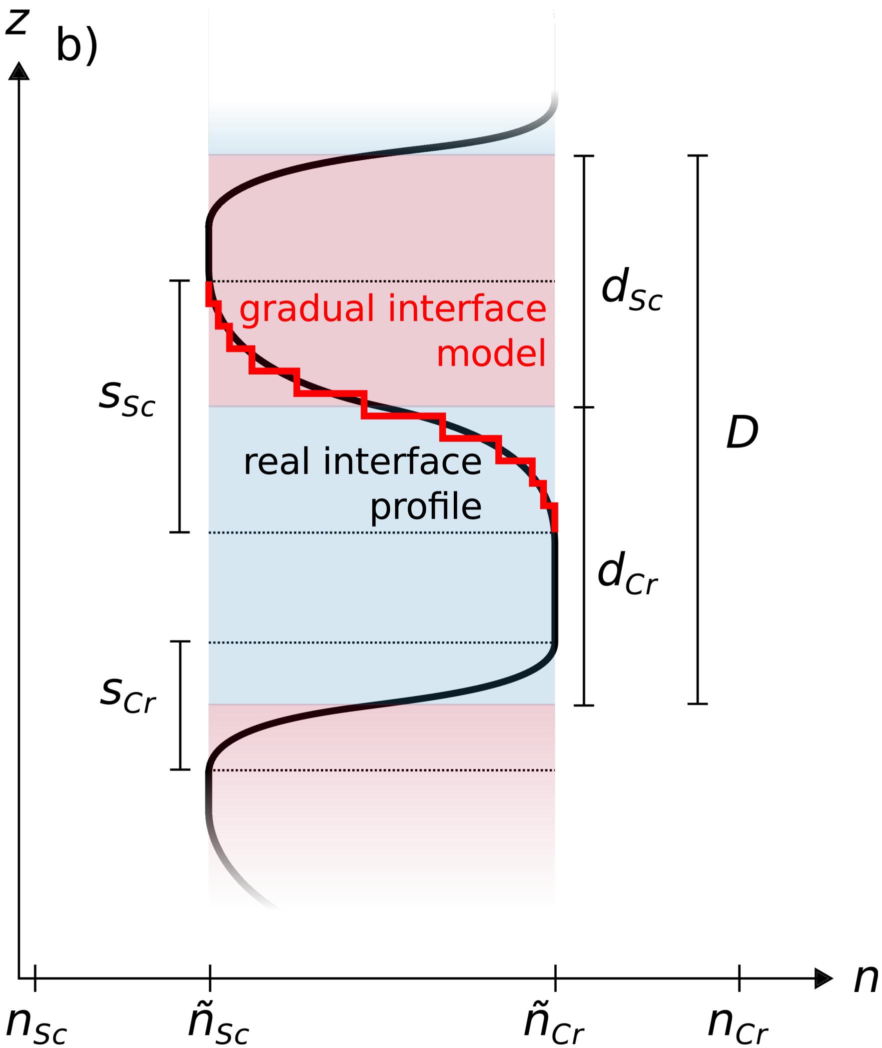


Binary Model with only
Nevot/Croce factor fails



Graded interface
model needed?

Graded Interface Model

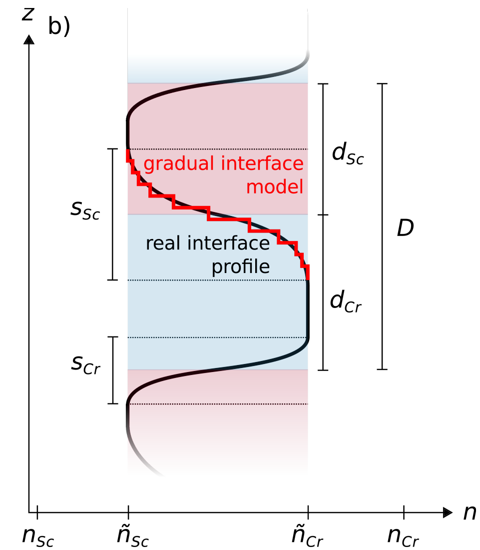


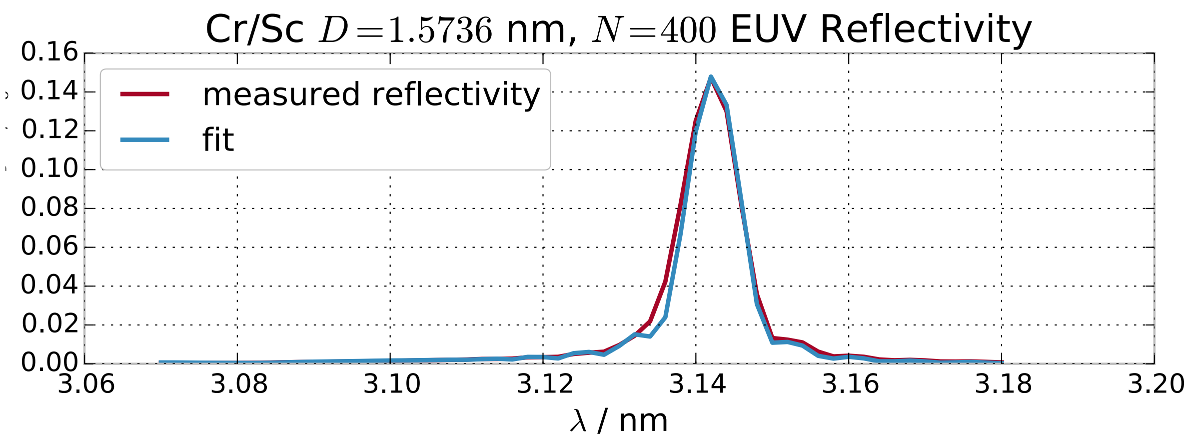
Graded interface model with explicit gradual changes at the interfaces and interdiffusion

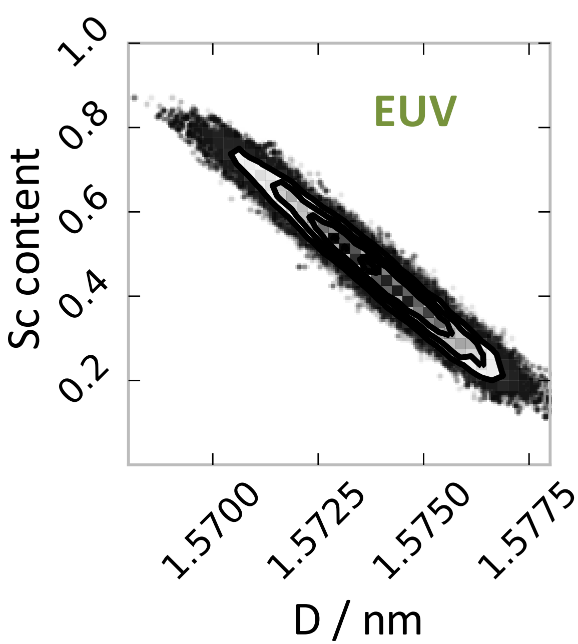
Parameter	Definition
D / nm	$= d_{\mathrm{Sc}} + d_{\mathrm{Cr}}$
Γ_{Sc}	$= d_{\mathrm{Sc}}/D$
s_d / nm	$= s_{\mathrm{Sc}} + s_{\mathrm{Cr}}$
Γ_s	$= s_{\mathrm{Sc}}/s_d$
η	layer intermixing
σ_r / nm	r.m.s. roughness
ρ_{Sc}	Sc density w.r.t. bulk density
ρ_{Cr}	Cr density w.r.t. bulk density

Analysis Strategy

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





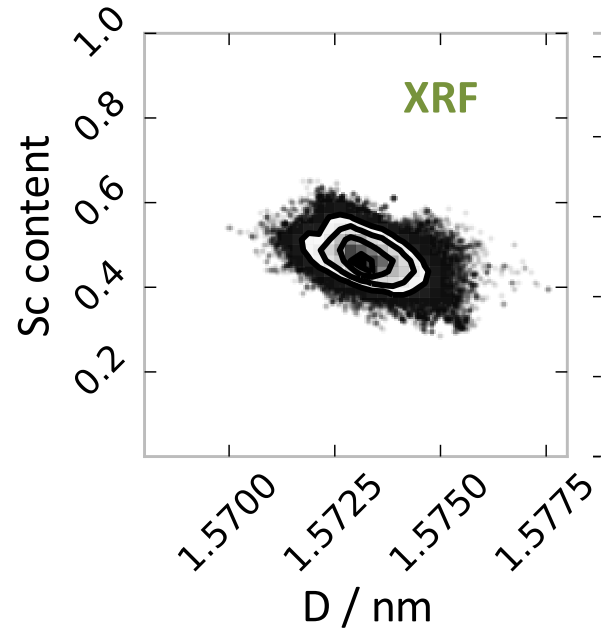


➡ fit based on particle swarm optimization followed by MCMC sampling

Analysis Strategy

Parameters:

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



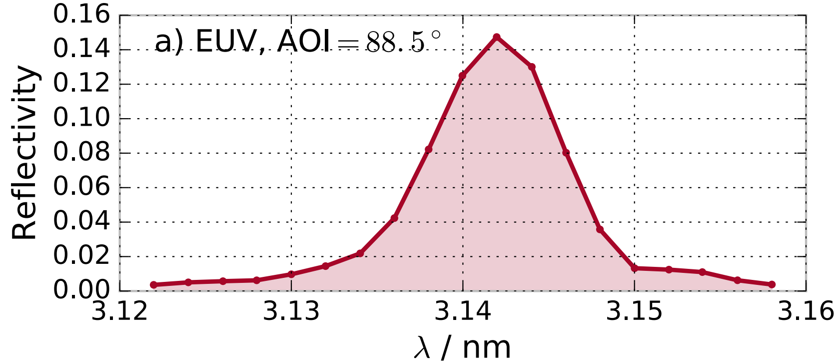
Combination of complementary methods:

- EUV reflectivity **(EUV)**
- Cu K-α **XRR**
- Resonant EUV reflectivity (across Sc L-edge) **(REUV)**
- X-ray fluorescence analysis (X-ray standing wave, **XSW**)

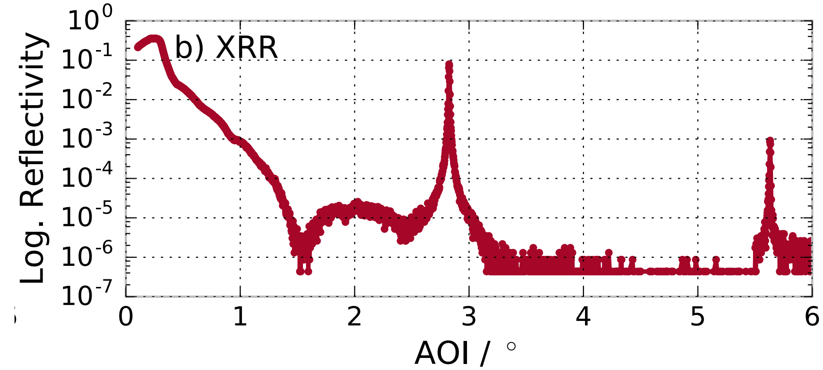
➡ Combined fit based on particle swarm optimization

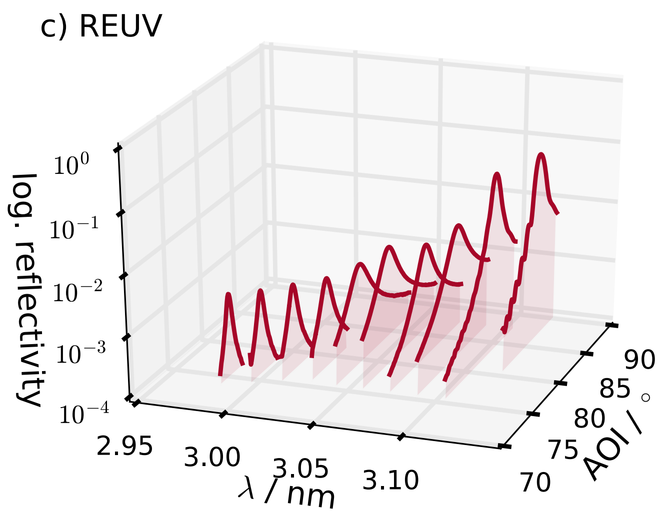
Complementary Experiments

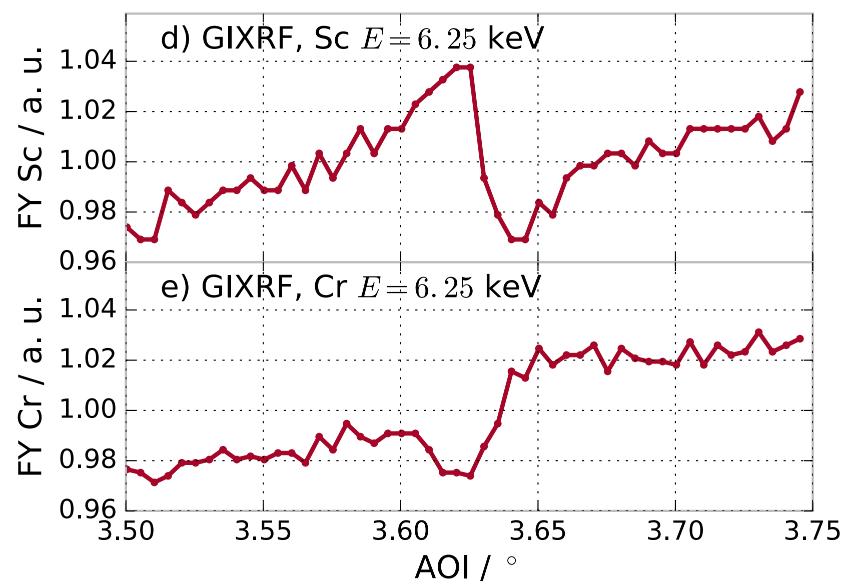
EUV reflectivity **(EUV)**



Cu K-α **XRR**



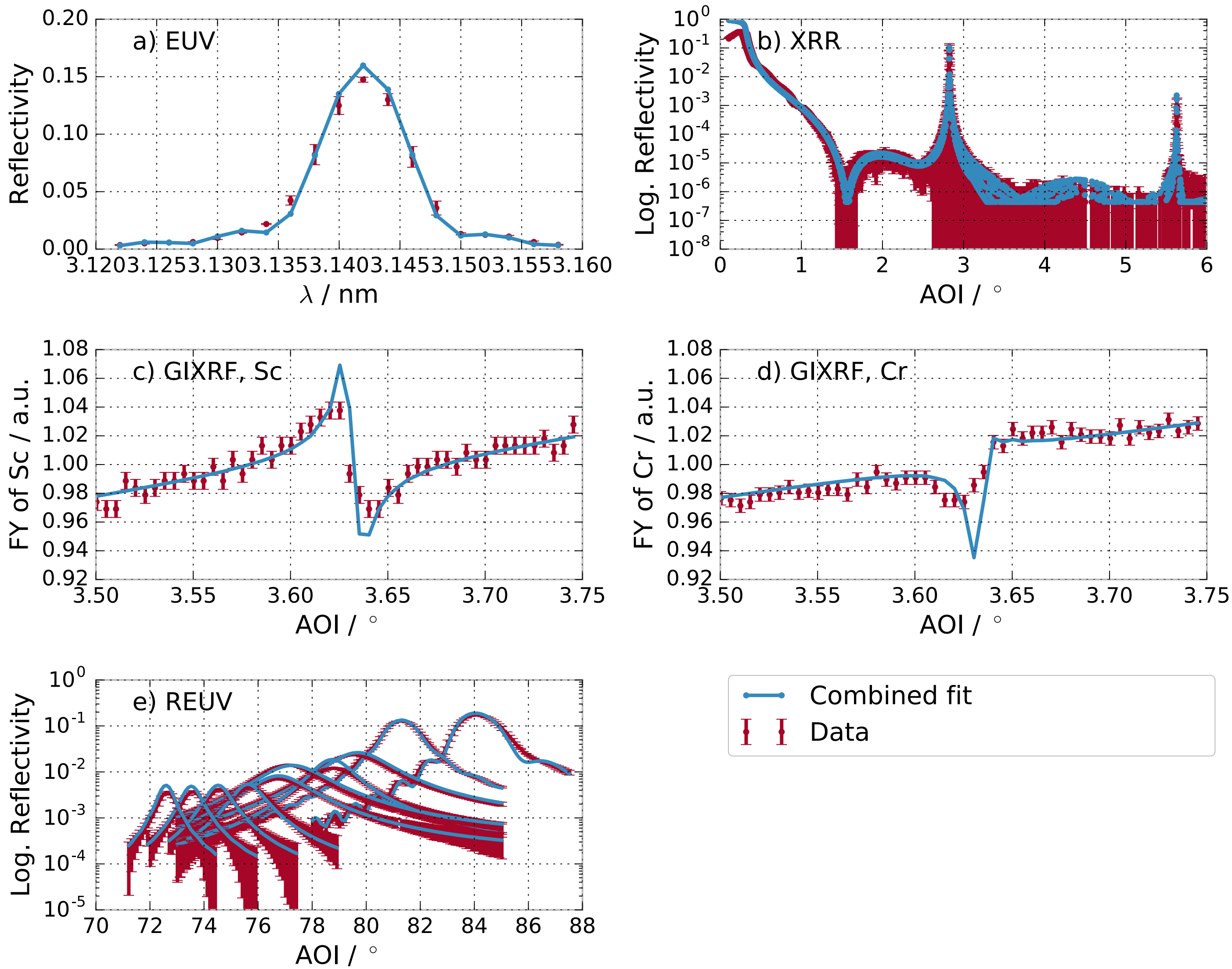




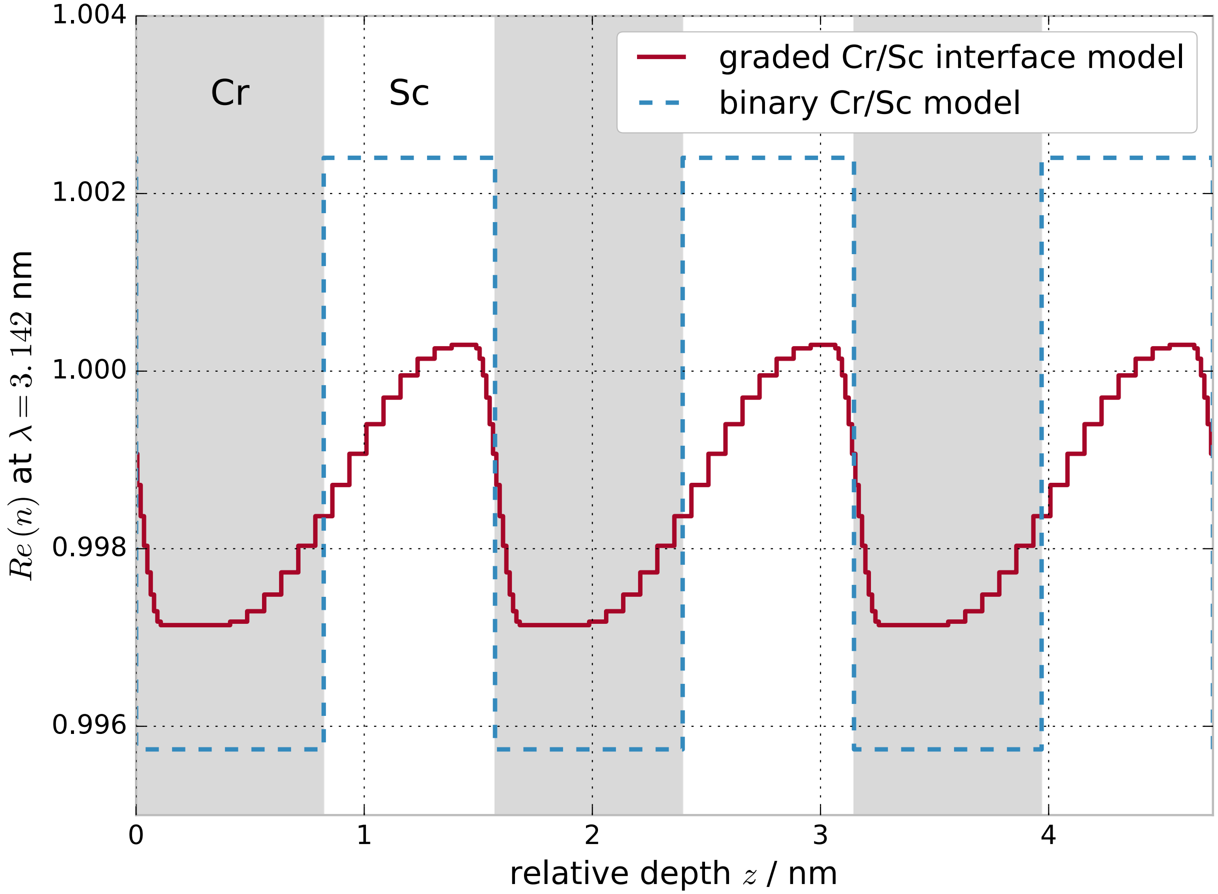
Resonant EUV reflectivity (across Sc L-edge) **(REUV)**

X-ray fluorescence analysis (X-ray standing wave, **XSW**)

Combined Analysis

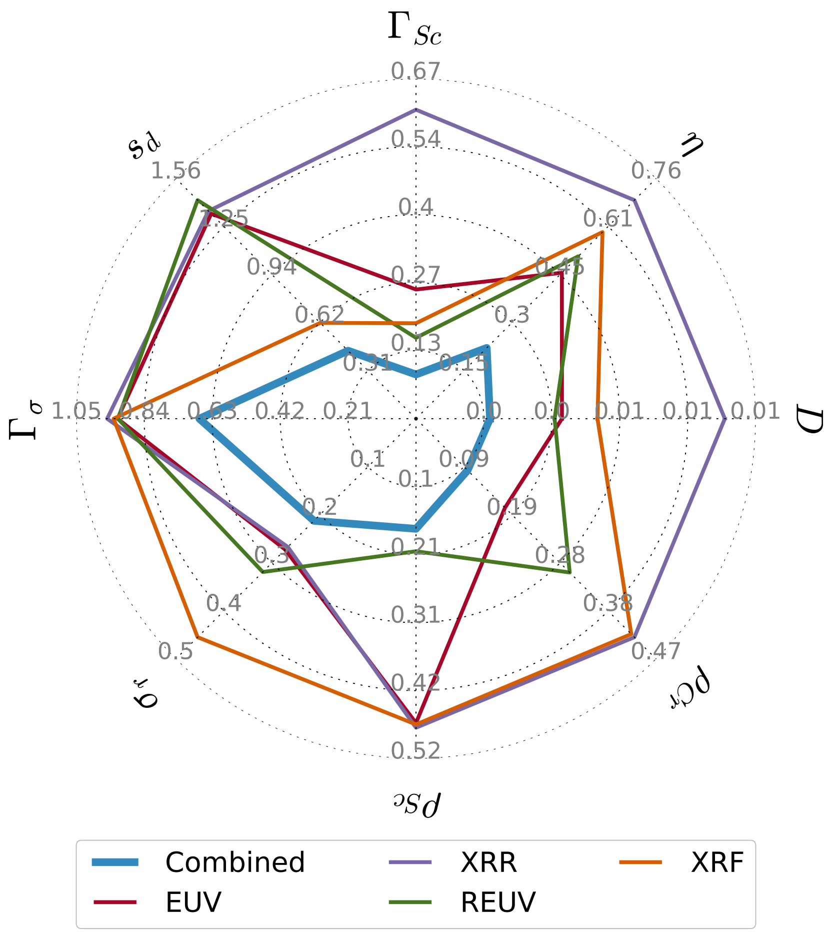


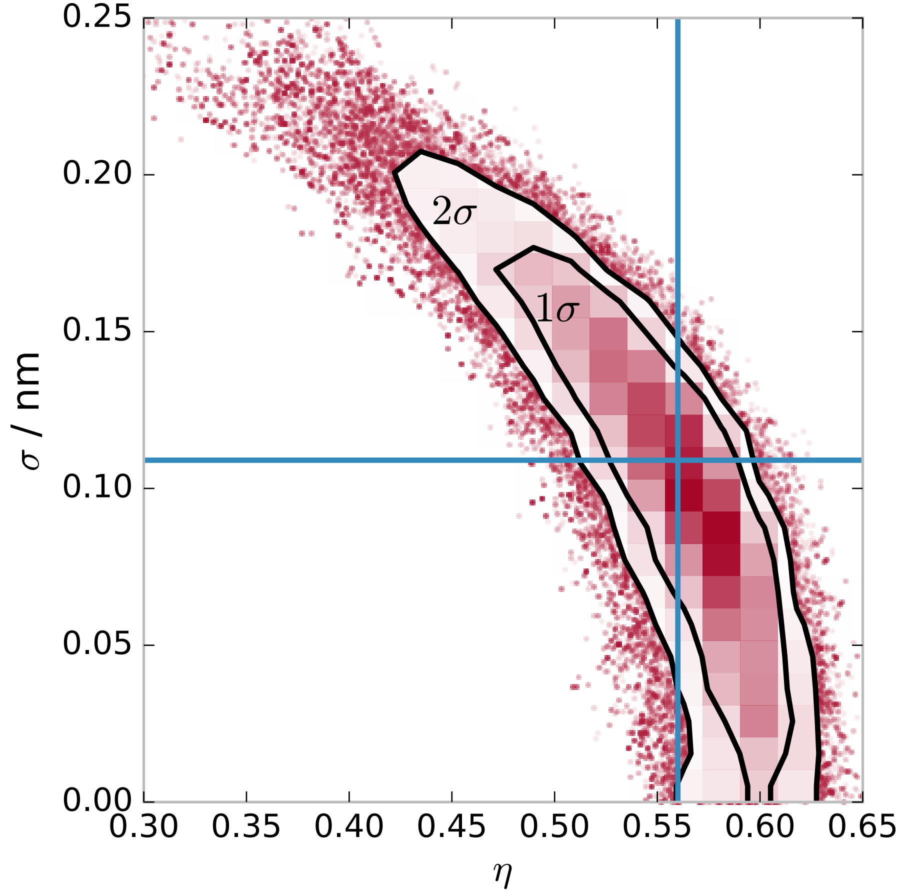
Consistent Model



- The two layers interdiffuse strongly (50-60 %)
- Asymmetric interface gradients

Confidence Intervals





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

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

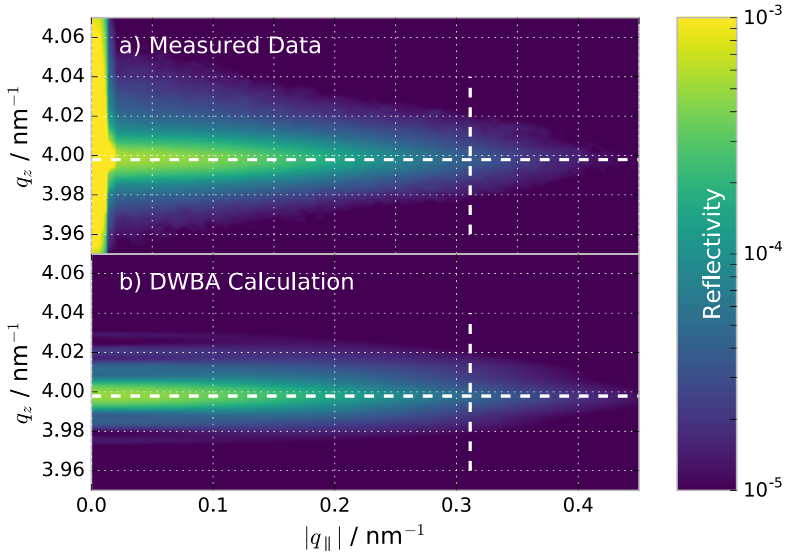
$$c_{ij}^\perp(q_x) = \exp\left(-\sum_{n=\min(i,j)}^{\max(i,j)} d_n/\xi_\perp(q_x)\right)$$

Integral PSD:

$$\sigma_r = \frac{1}{2\pi}\sqrt{\int_0^\infty q_\parallel C(q_\parallel)\,dq_\parallel}$$

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

Diffuse scattering

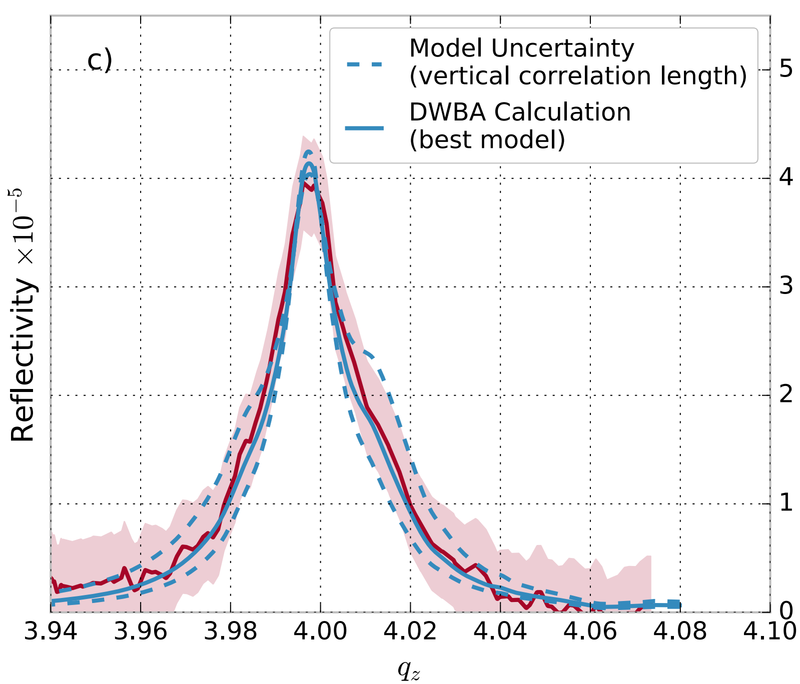


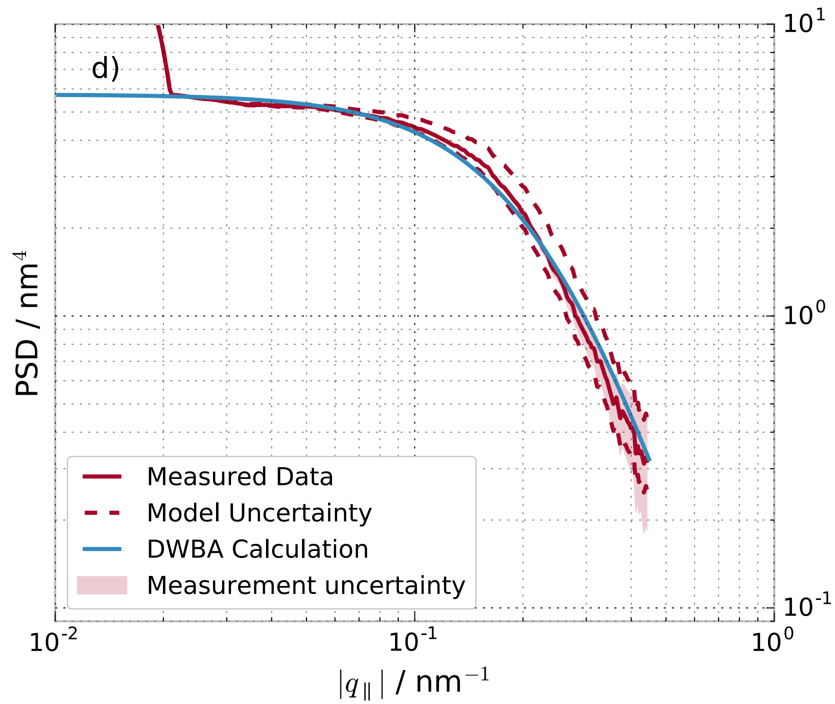
Integral PSD:

$$\sigma_r = \frac{1}{2\pi}\sqrt{\int_0^\infty q_\parallel C(q_\parallel)\, dq_\parallel}$$

Root mean square roughness:

$$\sigma_r = 0.17 \pm 0.02$$





Summary and Outlook

- The combination of several complementary methods is required to deduct a consistent model
- Ultra-thin multilayer systems require explicit modeling of the interfaces showing strong interdiffusion
- Roughness and interdiffusion can be distinguished by DWBA simulations based on the explicit model found above

A. Haase, S. Bajt, P. Hönicke, V. Soltwisch and F. Scholze:
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