Tungsten growth on silicon dioxide and boron carbide and additional role of spacer in the ultrashort period multilayer X-ray mirrors

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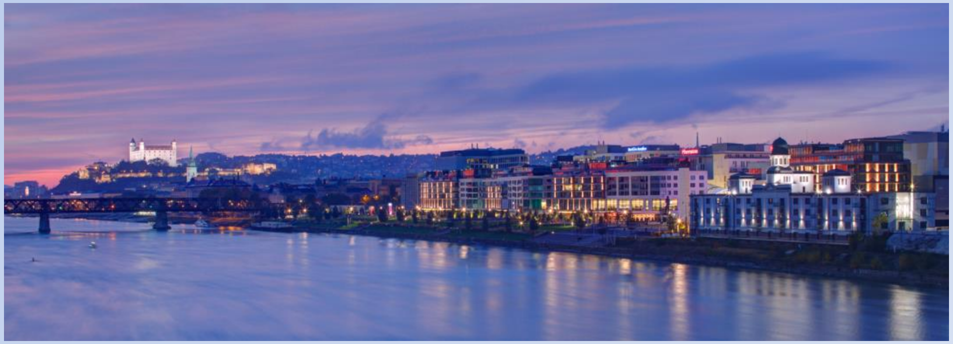
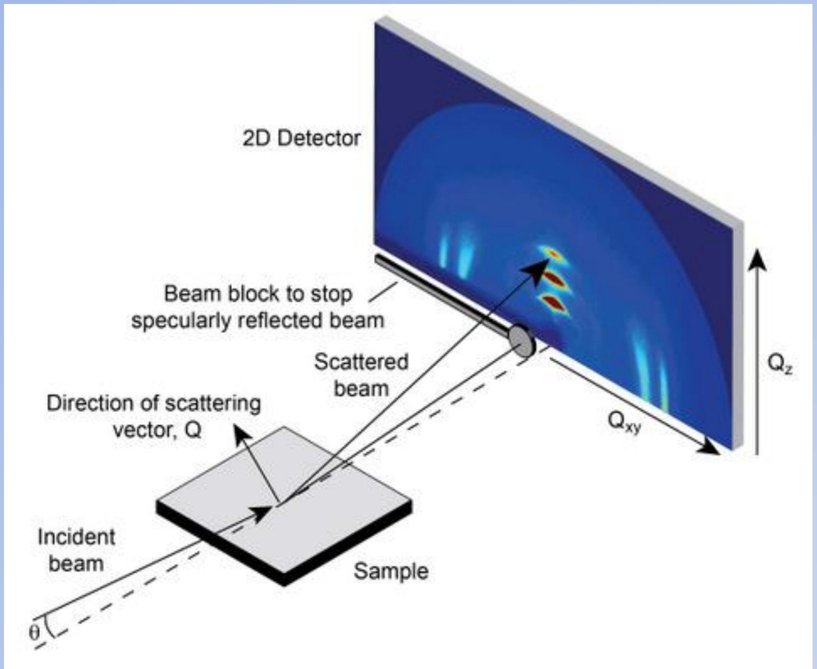
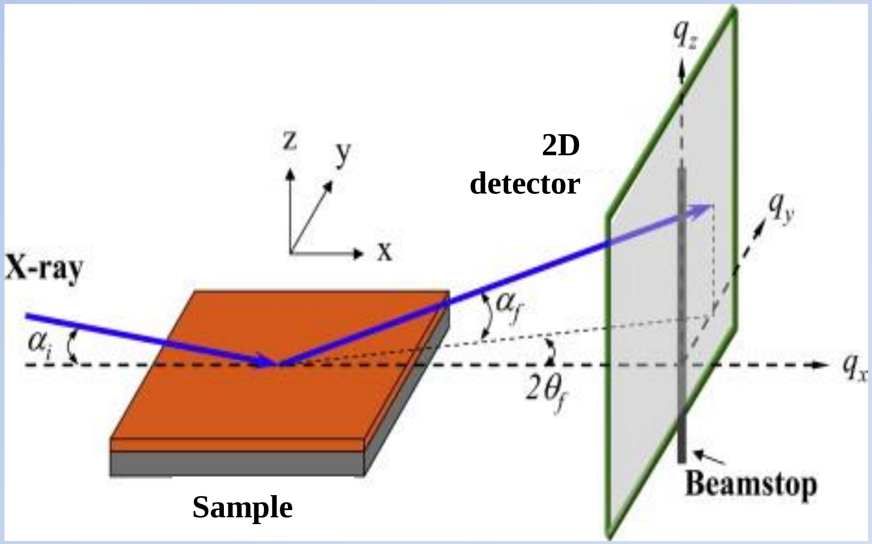
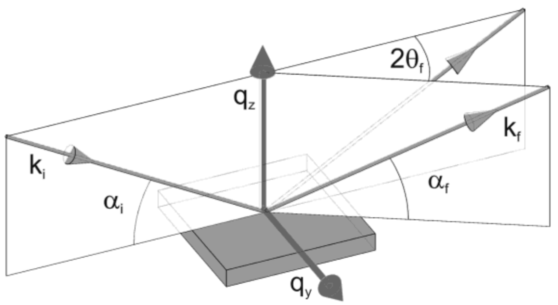


Grazing-incidence small-angle X-ray scattering (GISAXS)







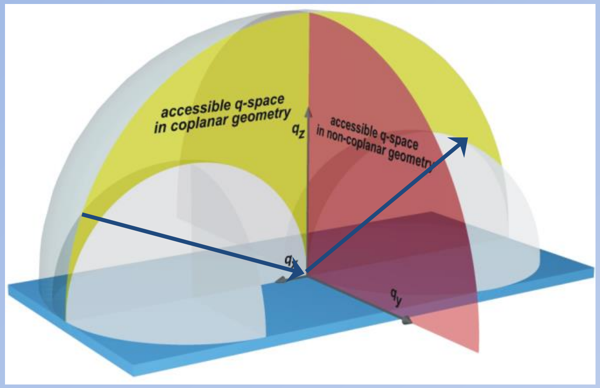
$$\vec{k} = \vec{k}_f - \vec{k}_i \quad \text{scattering vector}$$

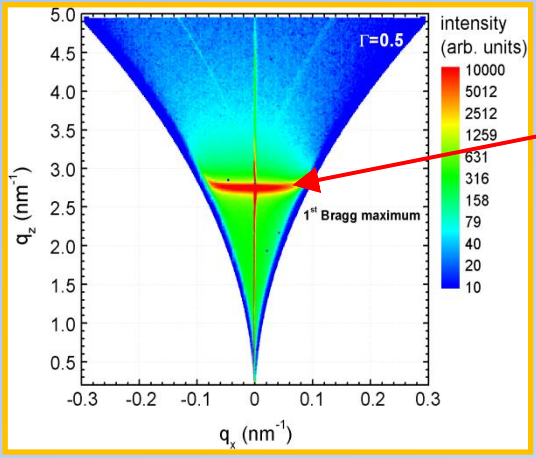
$$k_x = 2\pi/\lambda(\cos\alpha_f \cos 2\theta_f - \cos\alpha_i)$$

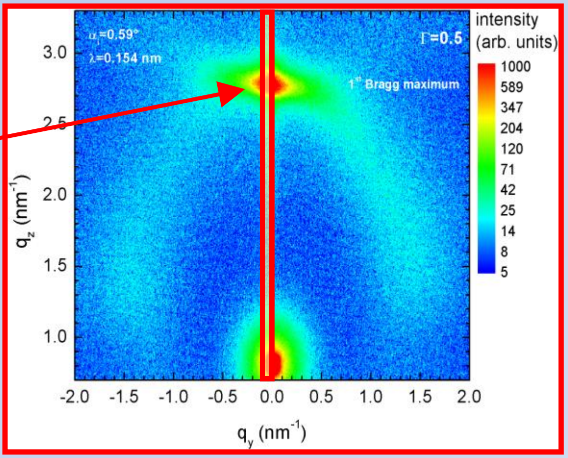
$$k_y = 2\pi/\lambda \cos\alpha_f \sin 2\theta_f$$

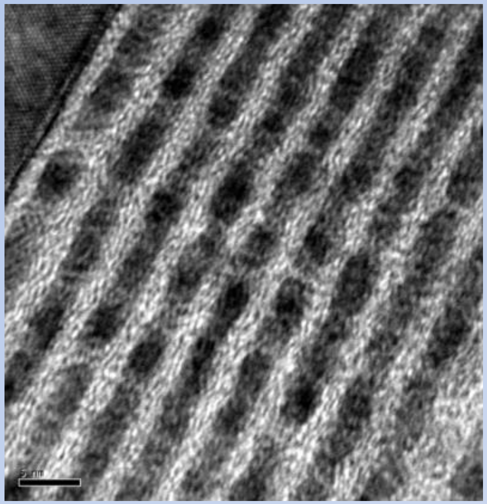
$$k_z = 2\pi/\lambda(\sin\alpha_f + \sin\alpha_i)$$

Coplanar versus non-coplanar geometry





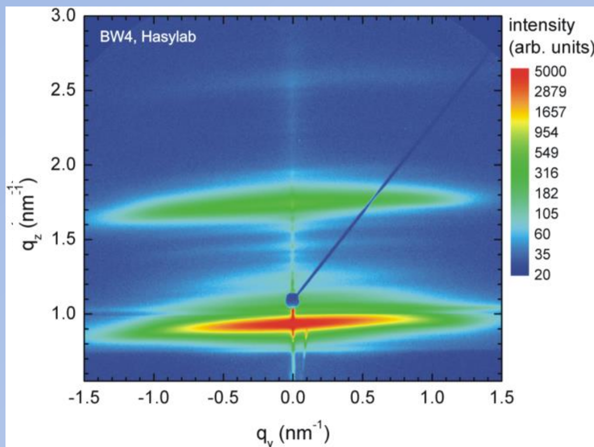




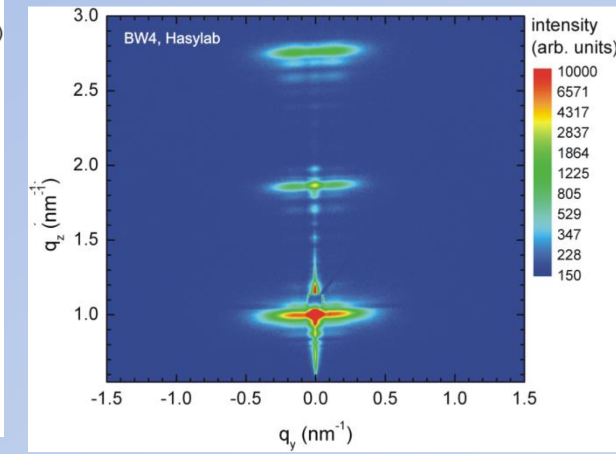
Co/C mirror for water window (d = 2.3nm, N = 200)
cross-sectional TEM reveals granular multilayer

GISAXS – fast probe of interface quality

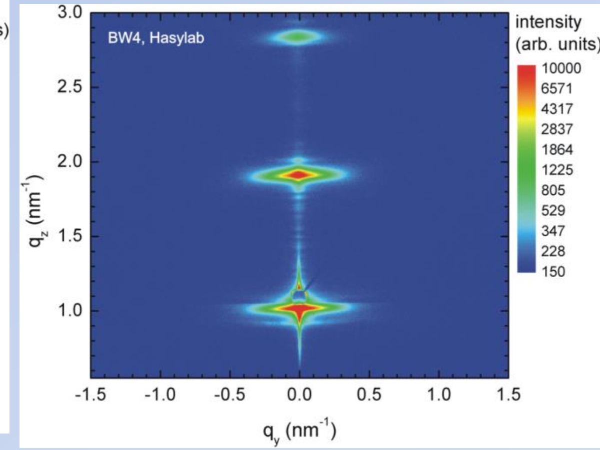
PVD



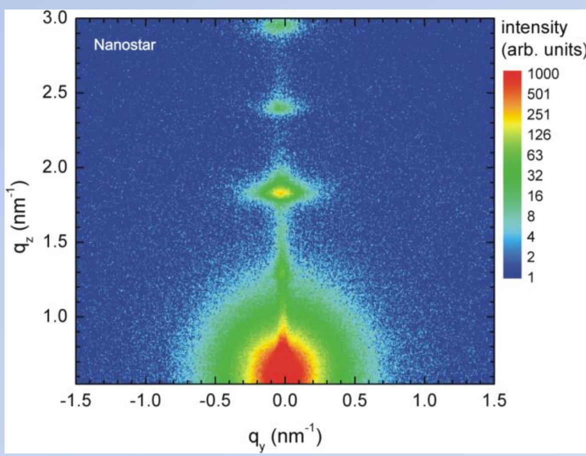
PVD@T=170°C



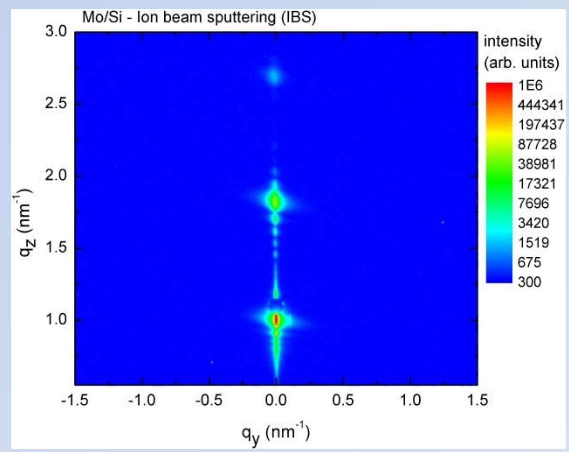
PVD/IB polishing



RF sputtering



ion beam sputtering



Mo/Si mirrors for EUV lithography

Grazing-incidence small-angle X-ray scattering (GISAXS)

$$\mathrm{CuK}_{\alpha} \qquad \alpha_i = \alpha_f = 0.7^\circ \qquad 2\theta_f = 1^\circ$$

$$k_x \triangleq -0.006\ nm^{-1} \rightarrow \Lambda_x \triangleq 1011\ nm$$

$$k_y \triangleq 0.7\ nm^{-1} \rightarrow \Lambda_y \triangleq 8.8\ nm$$

$$k_z \triangleq 1\ nm^{-1} \rightarrow \Lambda_z \triangleq 6.3\ nm$$

- nanometer-scale in-plane and in-depth resolutions are easily accessible
- lateral k_y and vertical k_z components of the scattering vector are independent of each other => simple BA theory is fully sufficient
- simple experimental arrangement
- intuitive shape of GISAXS pattern => modelling is not always necessary

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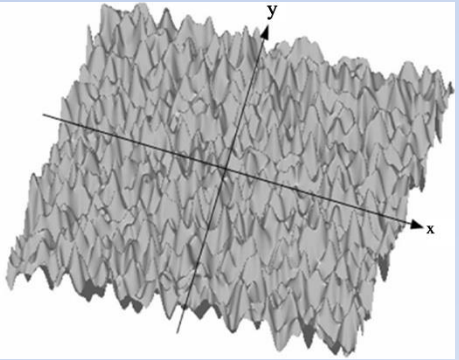
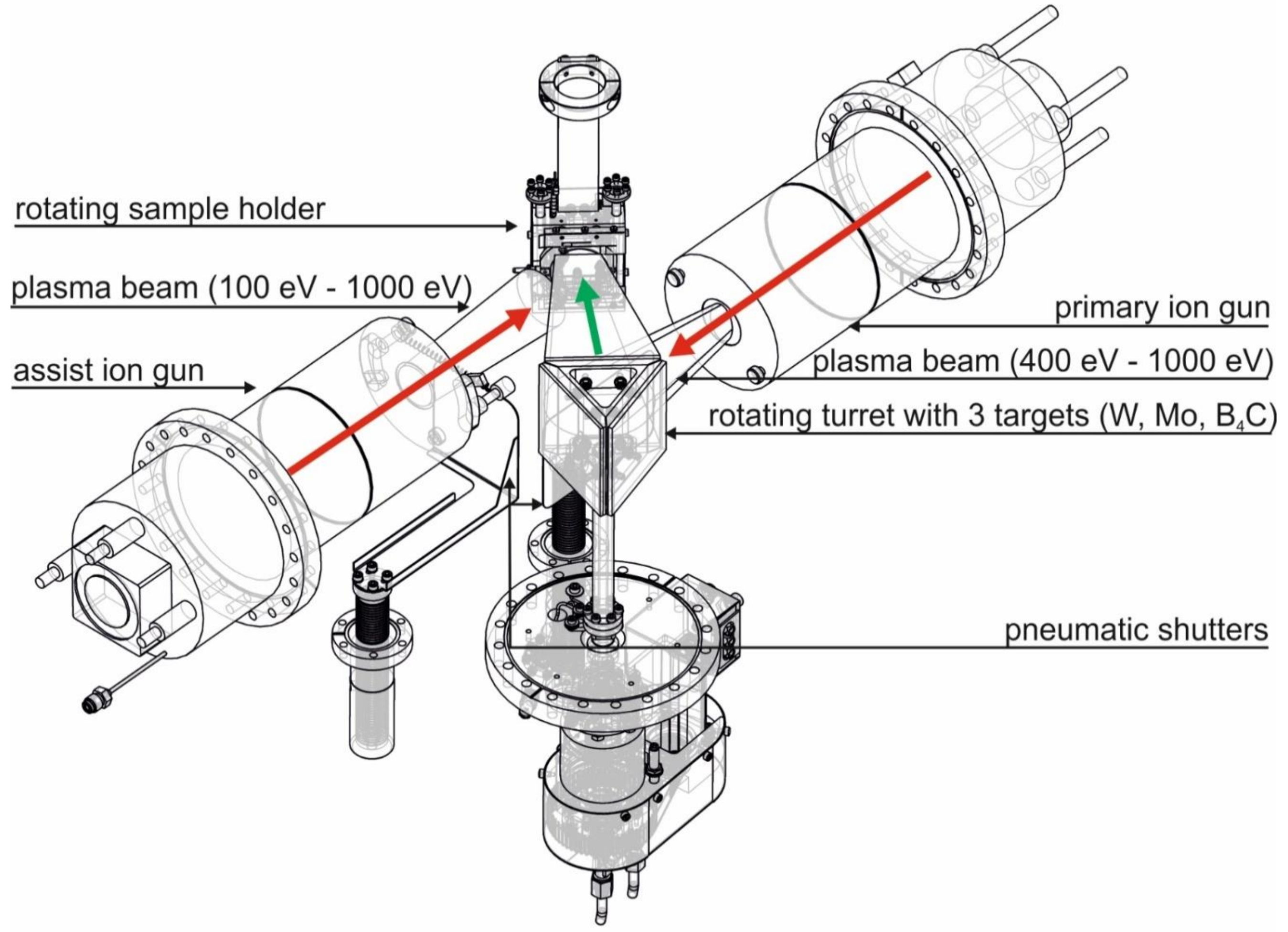
- GISAXS patterns provides FT of 2D autocorrelation function of the probed surface



Dual ion-beam sputtering system



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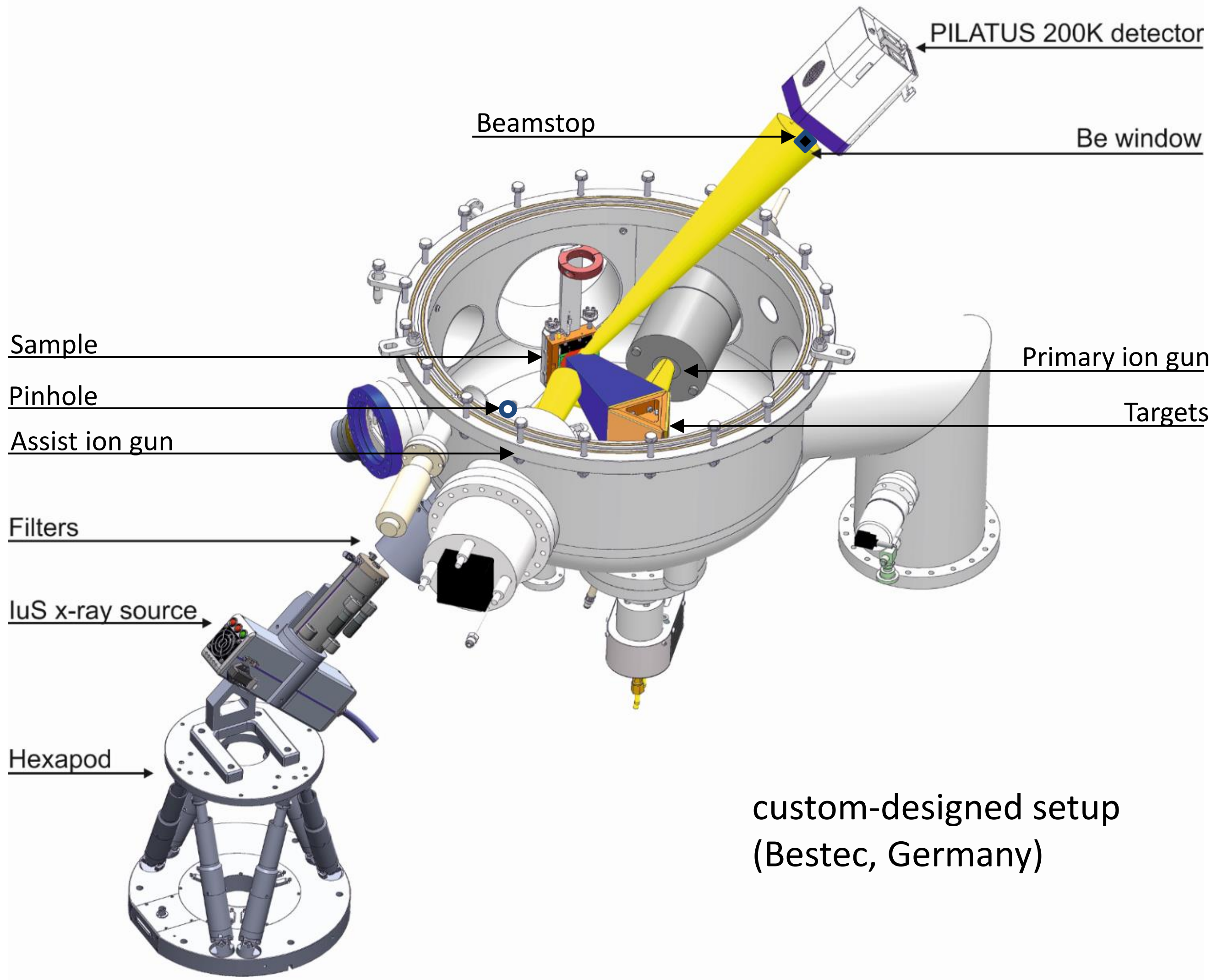
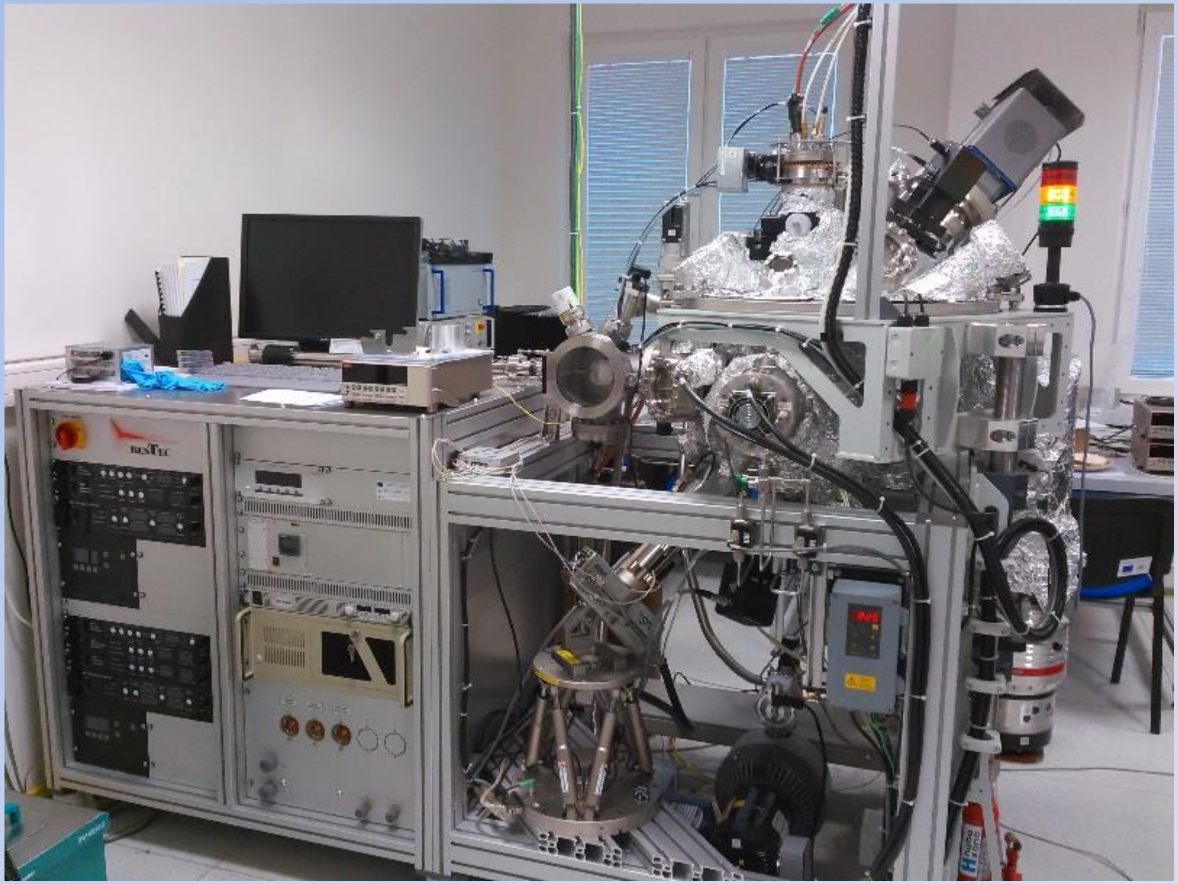


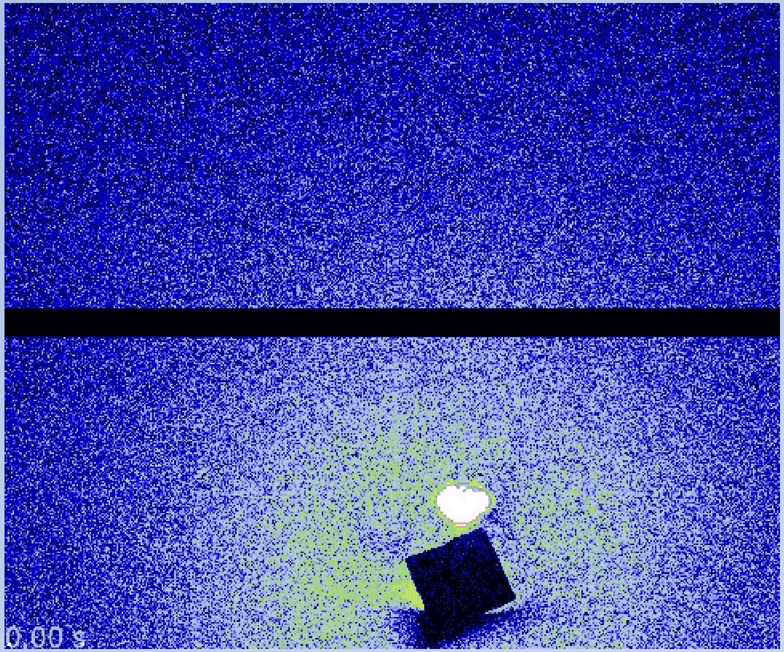
custom-designed setup
(Bestec, Germany)

Dual ion-beam sputtering system



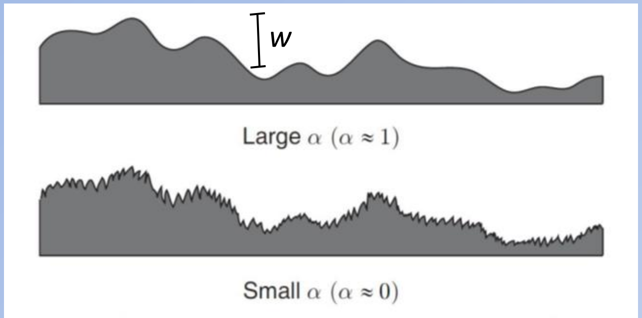
- 30 W microfocus X-ray source IμS (Incoatec), Cu K_{α} radiation
- X-ray detector Pilatus 200K (Dectris)
- total X-ray flux 1×10^8 ph/s

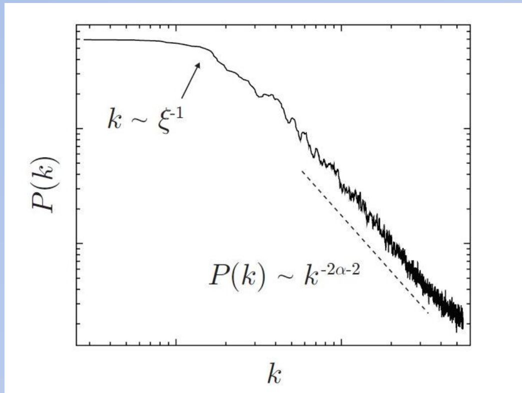
Multilayer mirror growth by in-situ GISAXS



W/B_4C mirror, 1.5 nm period, N=15
(d_W=0.6 nm, d_{B4C}=0.9 nm)
α_i = 0.25^O
deposition time ≈ 54 min.

Self-affine versus mounded surfaces



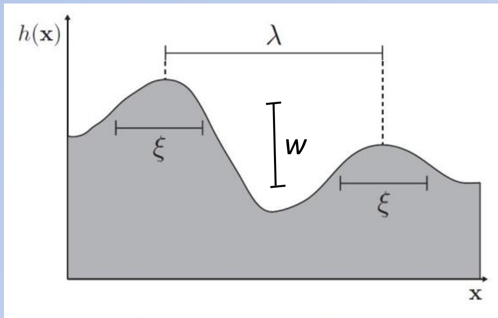


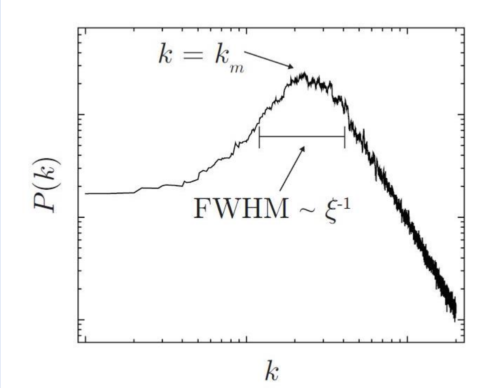
$$R(r) = \exp\left[-\left(\frac{r}{\xi}\right)^{2\alpha}\right]$$

$\alpha = 1$

$$\mathrm{PSD}(k) = \frac{w^2\xi^2}{4\pi}\exp\left[-\frac{k^2\xi^2}{4}\right]$$

α – fractal (Hurst) parameter

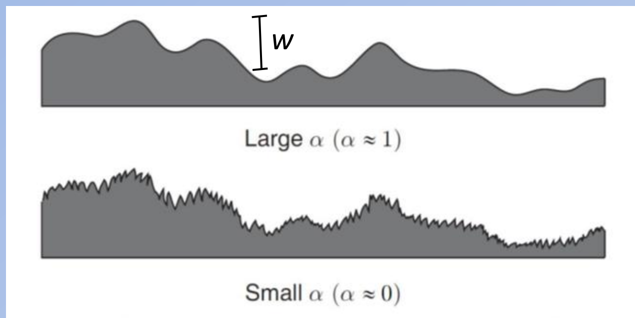


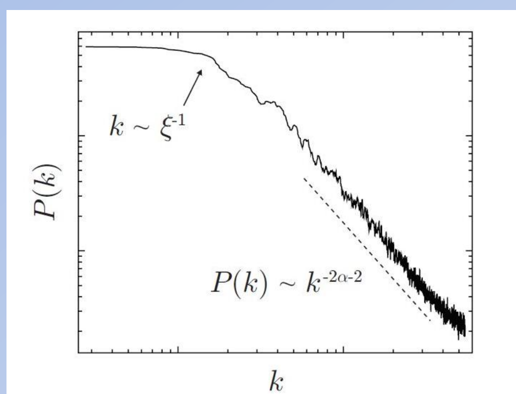


$$\mathrm{PSD}(k) = \frac{w^2\xi^2}{4\pi}\exp\left[-\frac{(4\pi^2 + k^2\lambda^2)\xi^2}{4\lambda^2}\right] J_0\left(\frac{\pi k \xi^2}{\lambda}\right)$$

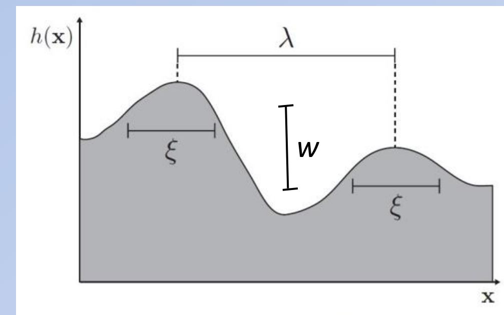
w – interface width (surface rms roughness)
ξ – lateral correlation length
λ – mound period (inter-cluster distance)
J_0 – Bessel function of zero order

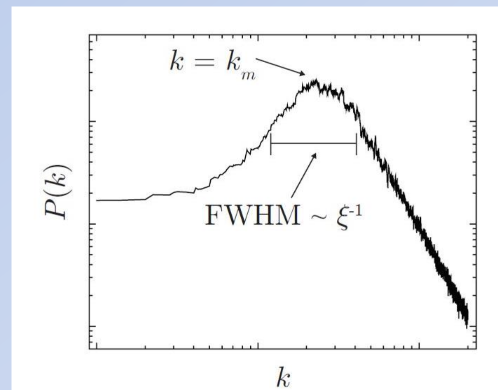
Self-affine versus mounded surfaces





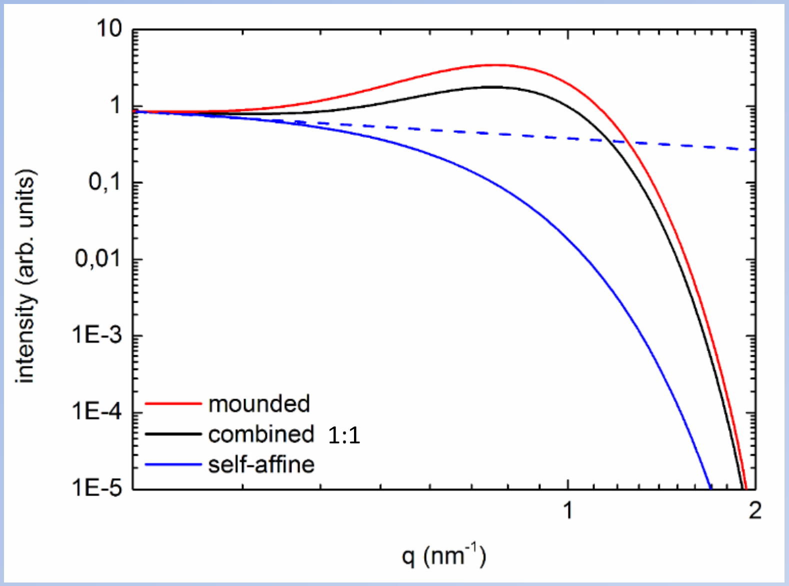
2D layer-by-layer growth

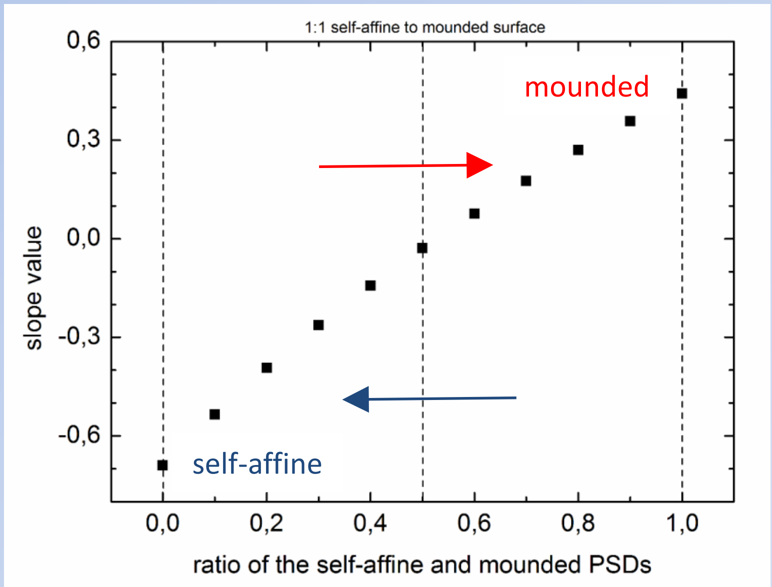




3D cluster growth

From self-affine to mounded surface





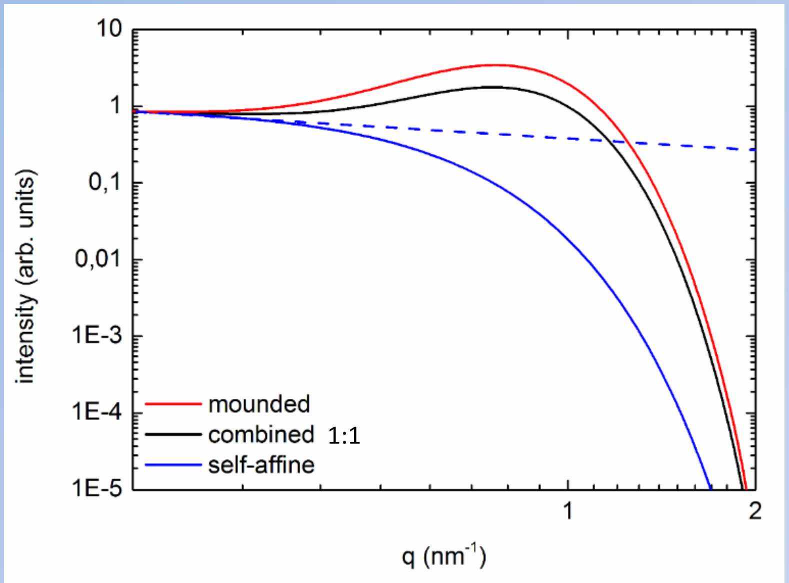
$m_1 \times PSD\ (k)^{self\text{-}affine} + m_2 \times PSD\ (k)^{mounded}$

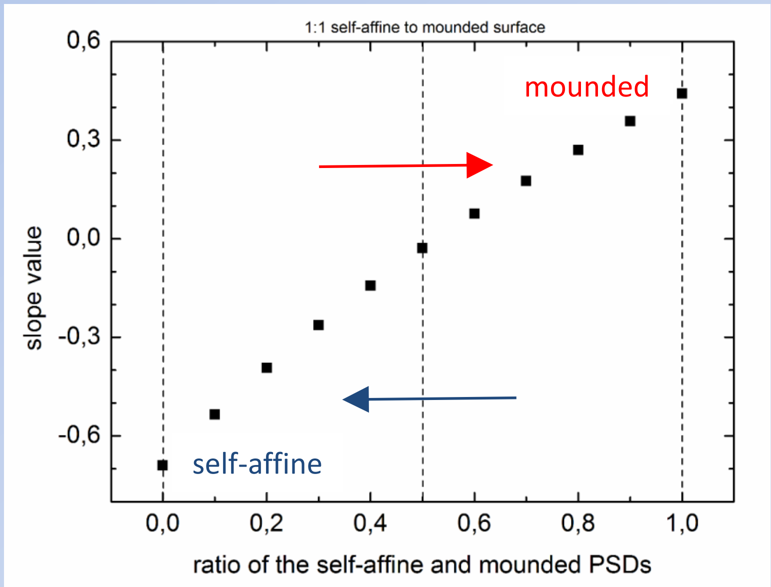
(w = 0.5nm, ξ = 5nm, λ = 5nm)

Initial slope values of PSD for different ratios of self-affine and mounded surfaces

slope < 0 => 2D growth
slope > 0 => 3D growth

From self-affine to mounded surface





$m_1 \times PSD\ (k)^{self\text{-}affine} + m_2 \times PSD\ (k)^{mounded}$

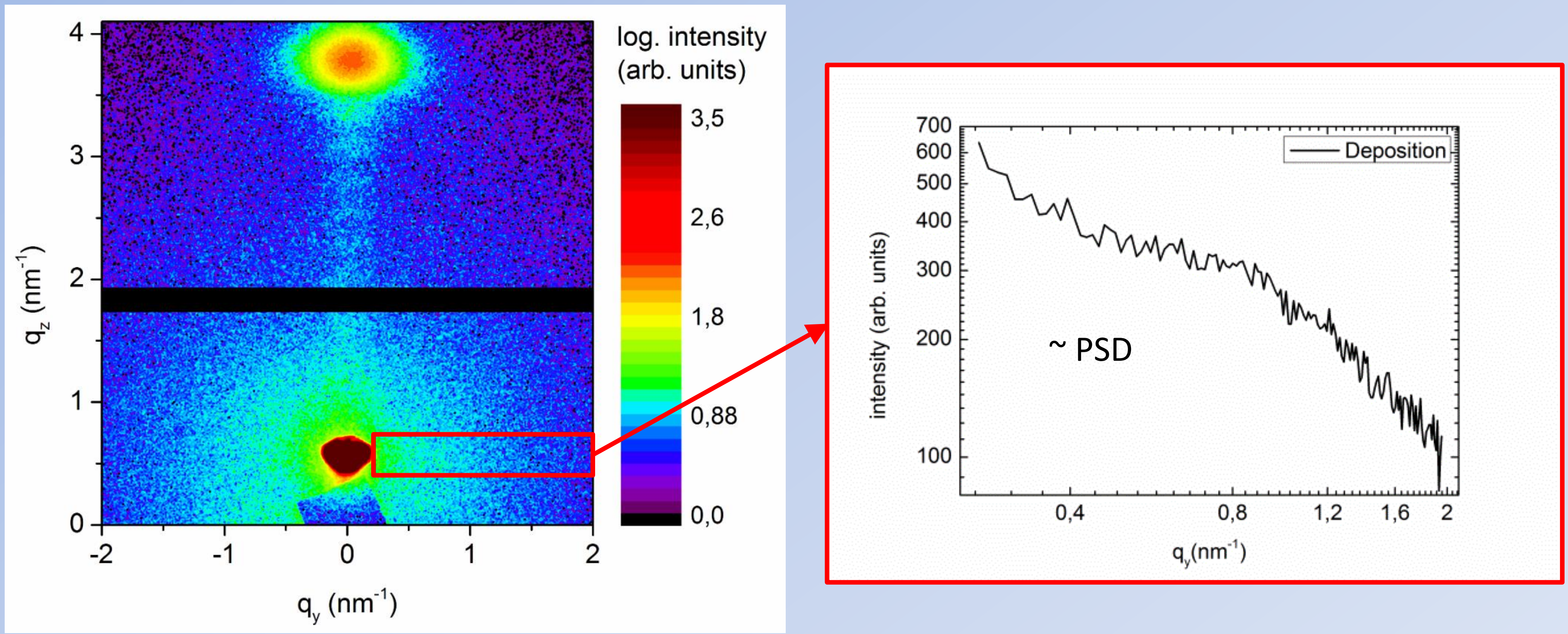
(w = 0.5nm, ξ = 5nm, λ = 5nm)

Initial slope values of PSD for different ratios of self-affine and mounded surfaces

ultra-short period multilayer
slope < 0

Power spectral density from GISAXS

W/B_4C multilayer on Si/SiO_2 substrate, d = 1.5 nm, N = 15, Γ = 0.33, α_i = 0.25^O



Lateral cut of GISAXS pattern at the exit angle close to the critical value for total reflection of the substrate is proportional to PSD function of the growing surface.

Power spectral density from GISAXS

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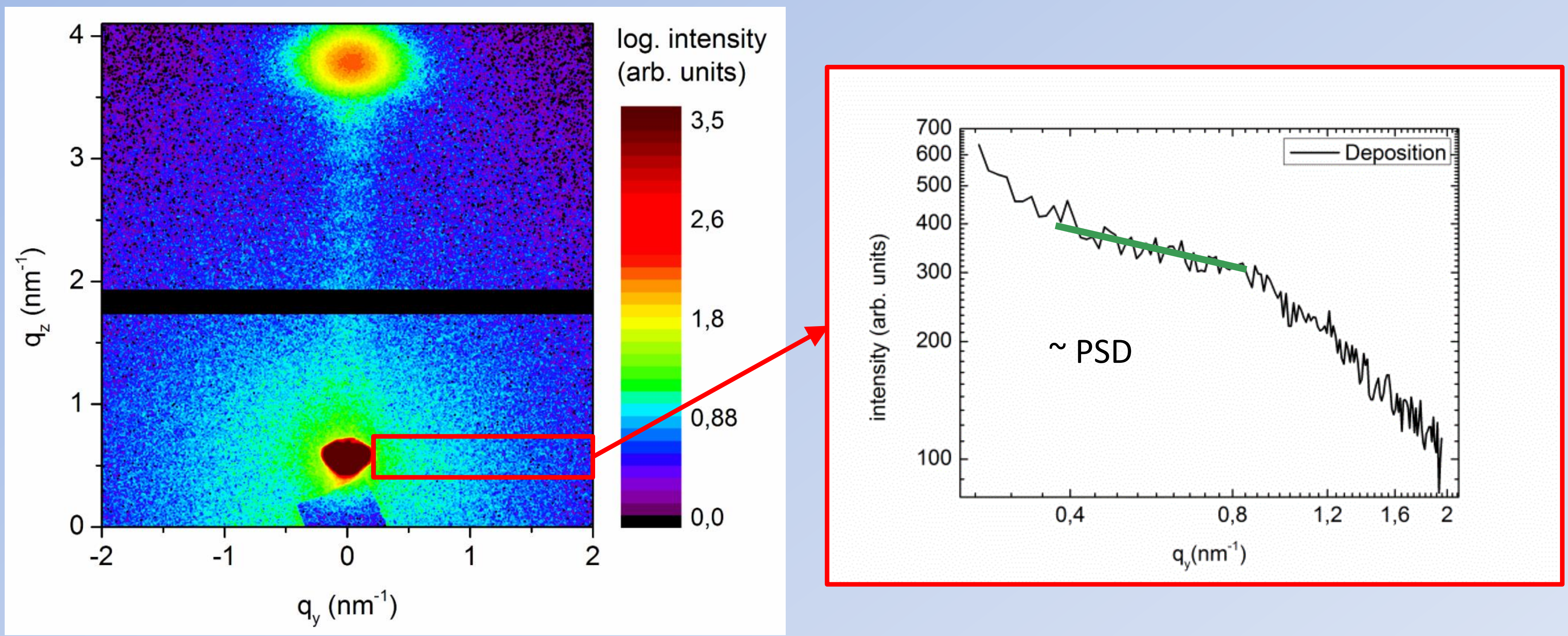
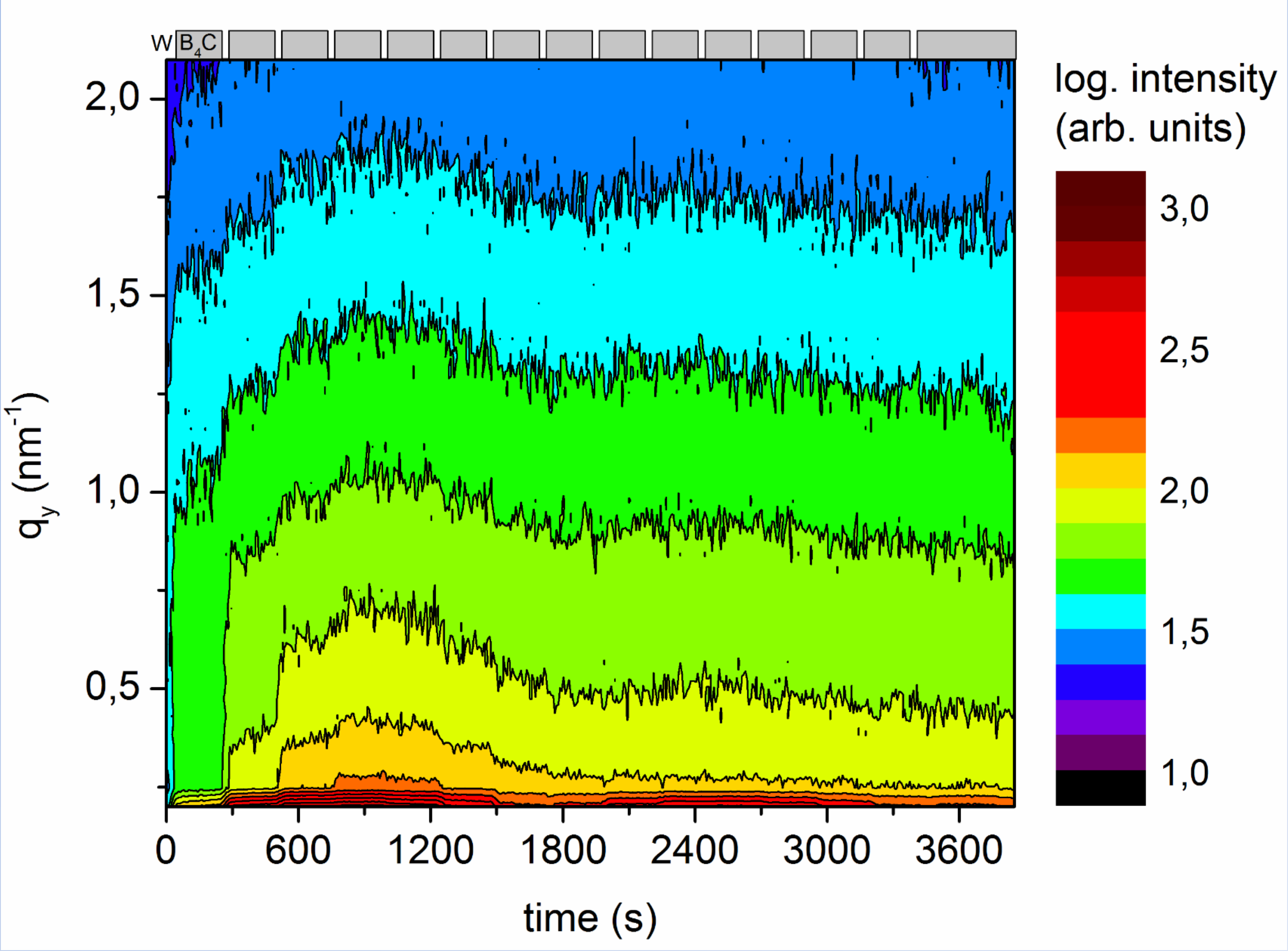
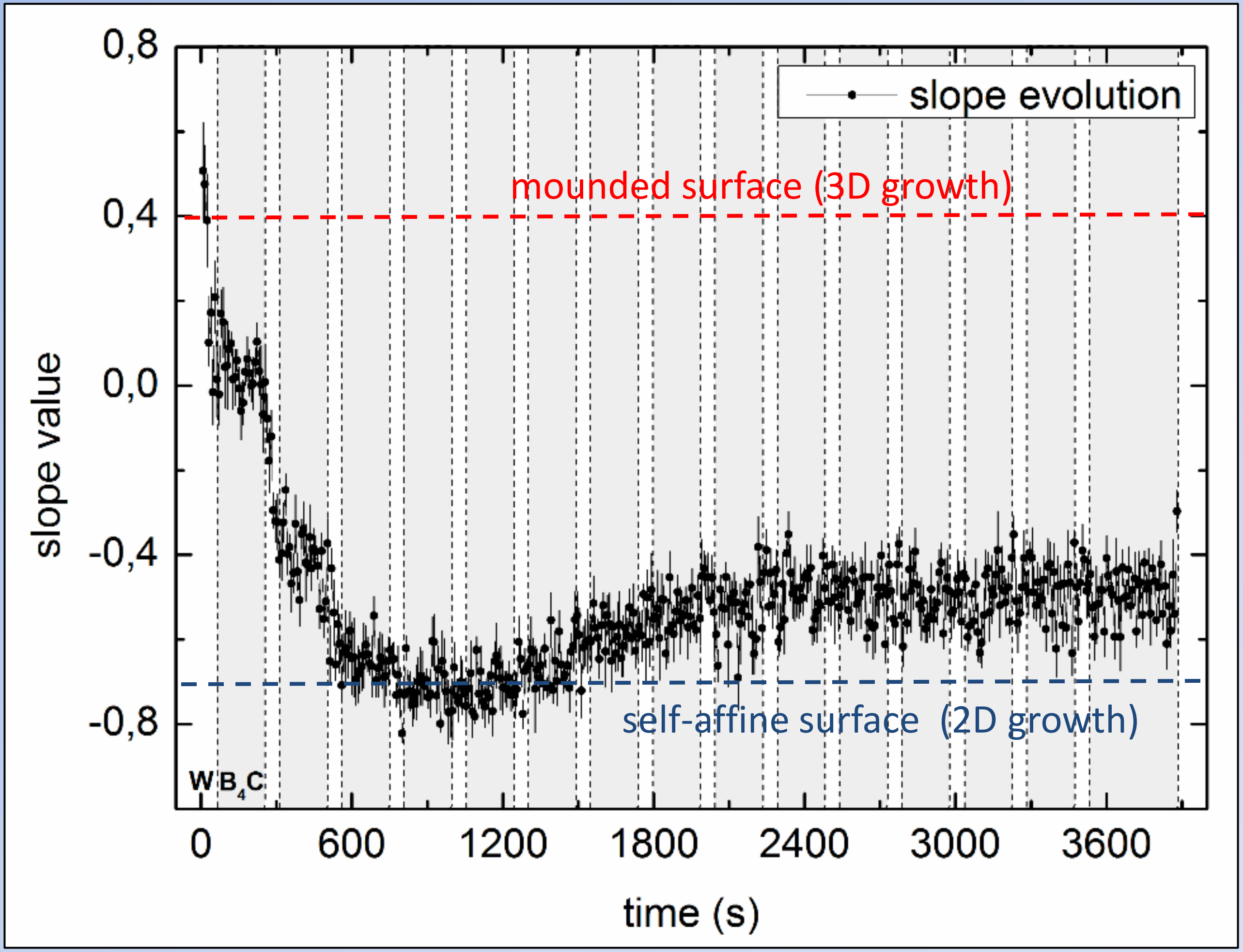


Lateral cut of GISAXS pattern at the exit angle close to the critical value for total reflection of the substrate is proportional to PSD function of the growing surface.

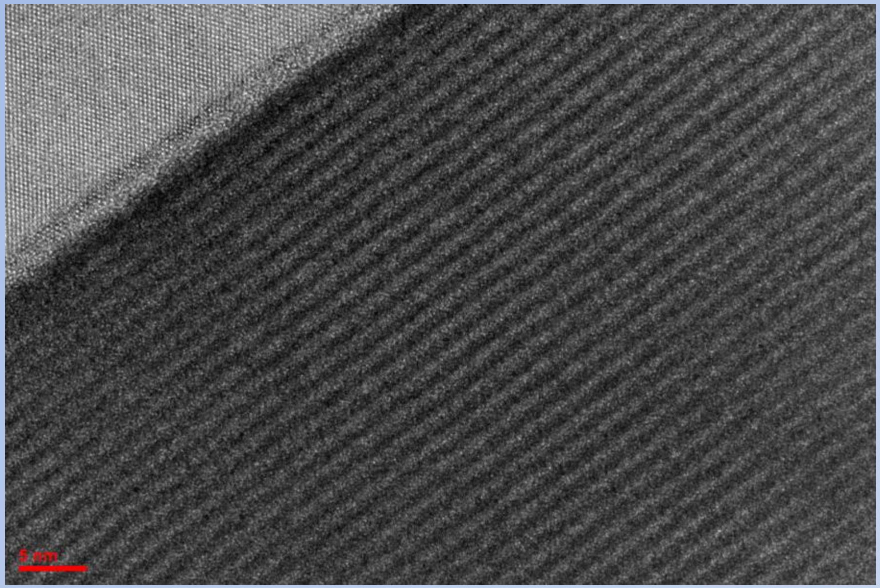
Temporal evolution of lateral cuts of GISAXS patterns

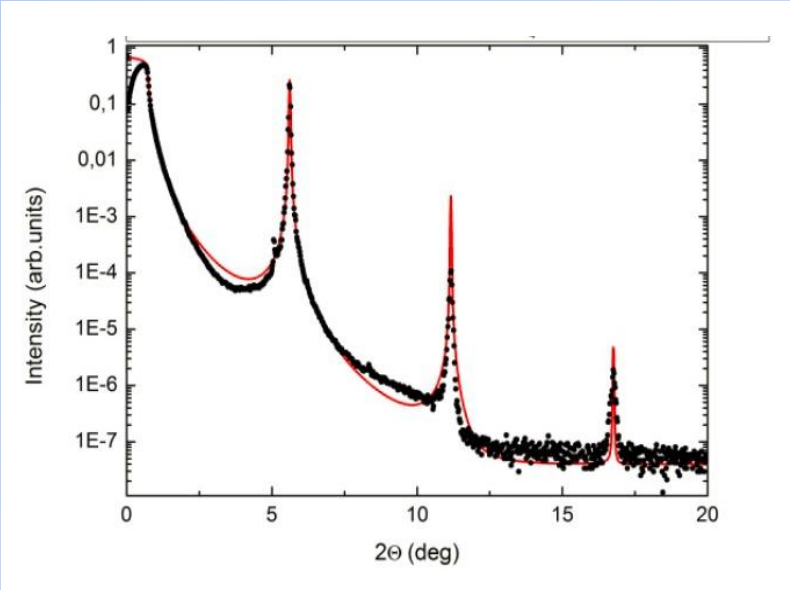


Temporal evolution of PSD slope derived from GISAXS



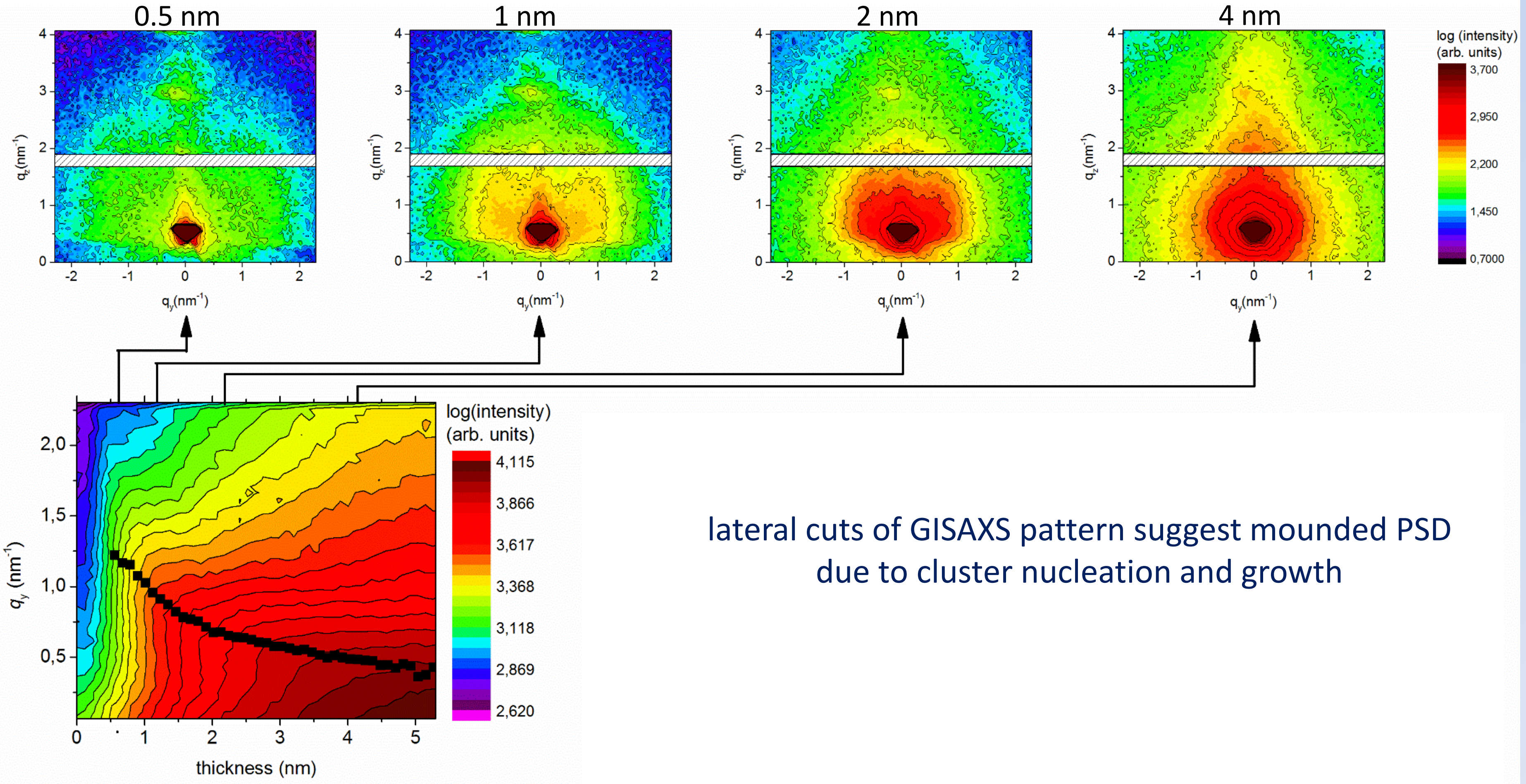
TEM, XRR





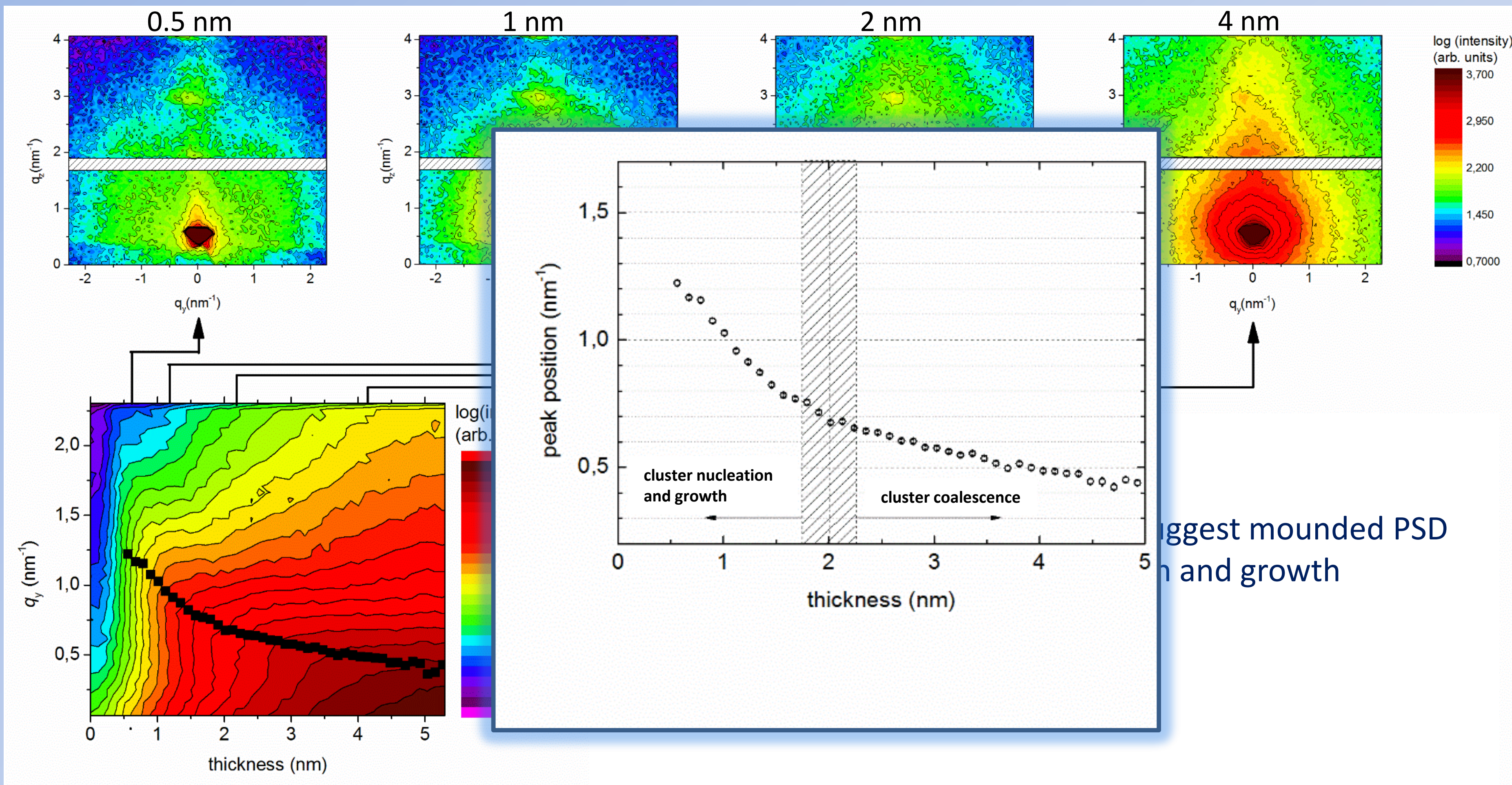
W/B_4C multilayer on Si/SiO_2 substrate, d = 1.5 nm, N = 300, Γ = 0.33, α_i = 0.25^O

3D growth of tungsten on SiO_2



lateral cuts of GISAXS pattern suggest mounded PSD due to cluster nucleation and growth

3D growth of tungsten on SiO_2



ggest mounded PSD
n and growth

Message

- Buildup of interfaces in W/B_4C mirrors is governed by an interplay between W agglomeration on SiO_2 and counteracting 2D layer-by-layer growth favored by B_4C.
- "Healing" effect of B_4C on the interface roughness plays a crucial role in the preparation of ultrashort-period multilayer mirrors without a need for additional interface treatment.
- In-situ GISAXS analysis revealed an additional role of the spacer beyond a merely optical one.
- Potential of laboratory-based in-situ GISAXS for analyses of multilayer growth was demonstrated using the latest-generation microfocus X-ray sources and fast 2D detectors.

Co-workers

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Martin Hodas
Institute of Applied Physics, University of Tübingen, Tübingen

Karol Végső
Japan Synchrotron Radiation Research Institute, Hyogo

Projects

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- European Research and Development Agency, ITMS 26220220170
- M-ERA.Net, XOPTICS
- Slovak Research and Development Agency, APVV-14-0745
- Grant Agency VEGA Bratislava, projects 2/0004/15

Thank you for your attention !