# Multilayer coatings for Synchrotron Radiation

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Our group has extensive experience in the fabrication and study of multilayer coatings, which are mainly used in X-ray optics as multilayer X-ray mirrors (MXMs).

These are conventional MXMs based on

- **Be** (Ti/Be),
- **B** (Mo/B, Mo/$B_4C$, Sb/$B_4C$, W/$B_4C$),
- **C** (Si/C, Co/C, Ni/C, W/C, Cr/C),
- **Mg** (Zr/Mg, Si/Mg),
- **Si** (Sc/Si, Mo/Si, W/Si),
- **Sc** (Cr/Sc, W/Sc) and
- **Ti** (W/Ti),

as well as heat- and radiation-resistant MXMs: Si/$Mg_2Si$, $Mo_2B_5$/$B_4C$, $MoSi_2$/Si, WC/Si, $CrB_2$/C, etc.

We have fabricated

- mirrors,
- monochromators,
- collimators,
- polarizers,
- objectives,
- diffraction gratings,
- supermirrors etc.

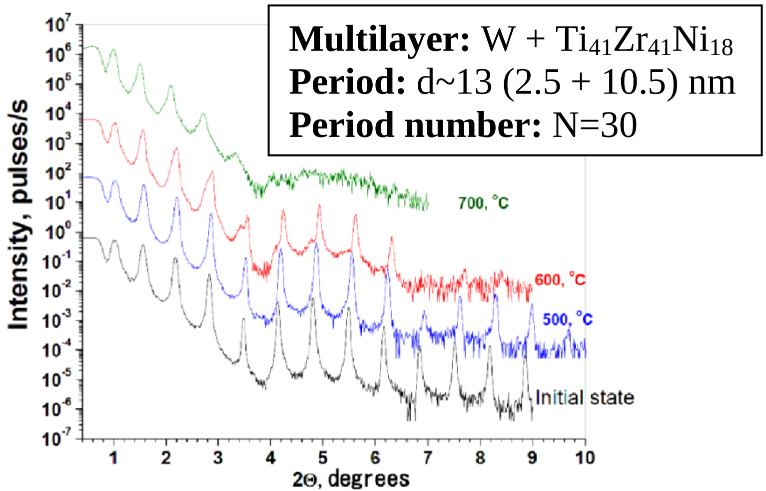
We have studied

- thermal and radiation stability of MXMs;
- early stage of reaction between layers at sub-nanometer level;
- have made estimation of thickness, composition and density of reaction products.

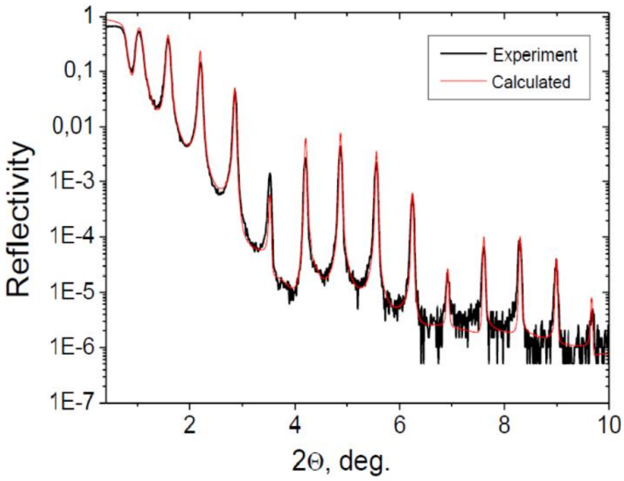
The following are some recent results on application of fabricated multilayers.

# Multilayers (MLs) for radiation-resistant materials in nuclear and thermonuclear power engineering

**ML: W + TiZrNi (quasi-crystal)**
**W** – small sputtering rate, high melting threshold, high heat conductivity
**Quasi-crystal** (QC) – reduces the impact of hydrogen on tungsten and steel



Small-angle X-ray reflectivity (λ=0.154 nm) for the W/QC ML (d=13 nm, N=30) in the initial state and after annealing at 500°C, 600°C, and 700°C in vacuum.



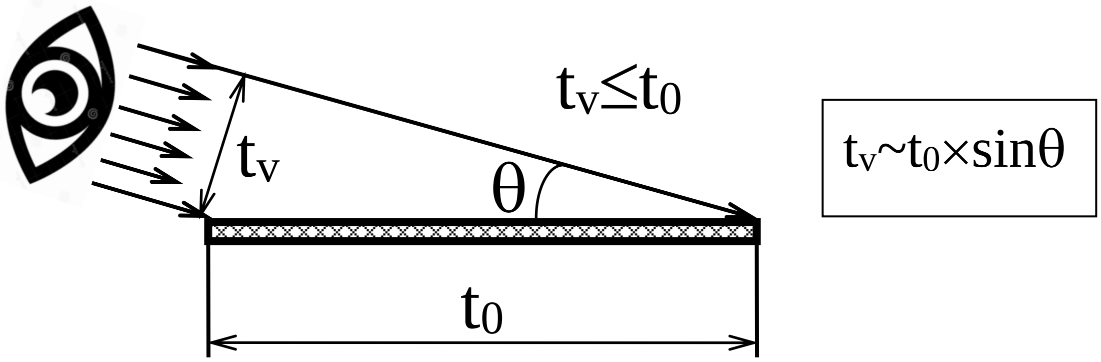
Measured and calculated small-angle X-ray reflectance (λ=0.154 nm) for the W/QC ML (d=13 nm, N=30) after annealing at 500°C

**Results of calculations (T=500°C)**

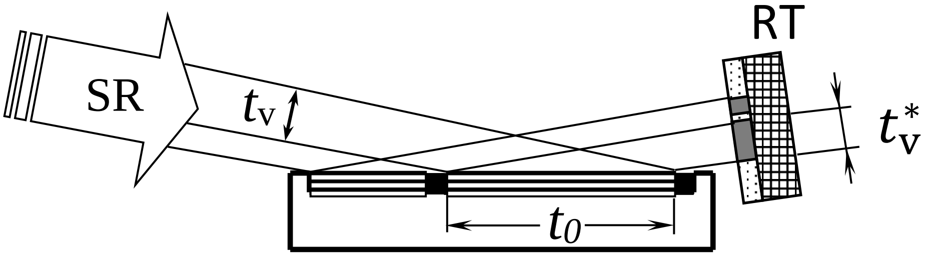
| **Layers** | **Materials** | **Thickness** nm | **Density** g/cm3 | **Roughness** nm |
|---|---|---|---|---|
| **top layer** | W | 2.57 | 16.9 | 0.44 |
| **ML** (30 periods) | $Ti_{41}Zr_{41}Ni_{18}$ | 10.26 | 6.3 | 0.37 |
| | W | 2.57 | 17.8 | 0.32 |

**Reference**: O.Yu. Devizenko, I.A. Kopylets et al. “Multilayer tungsten/quasi-crystal Ti-Zr-Ni systems as promising materials of protective elements a fusion reactor”, Problems of Atomic Science and Technology, 2 (150), 28-33 (2024).

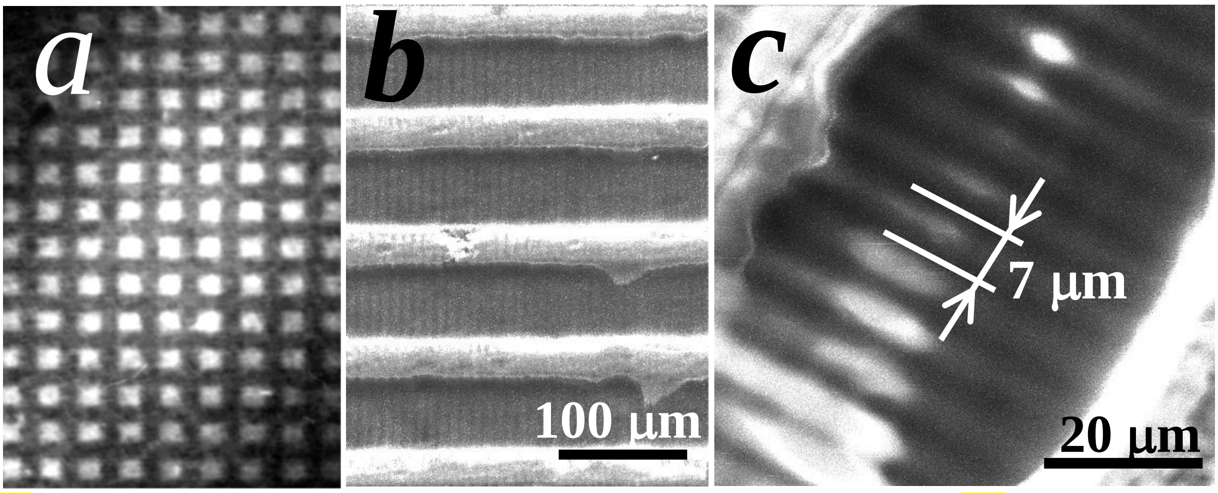
# Reflective multilayer (ML) X-ray masks



**A layout showing the principle of one-dimensional compression**



**Schematic drawing of a reflective X-ray mask and its application for normal exposure of the recording element surface** (**SR** – synchrotron radiation, **RT** – recording tool).

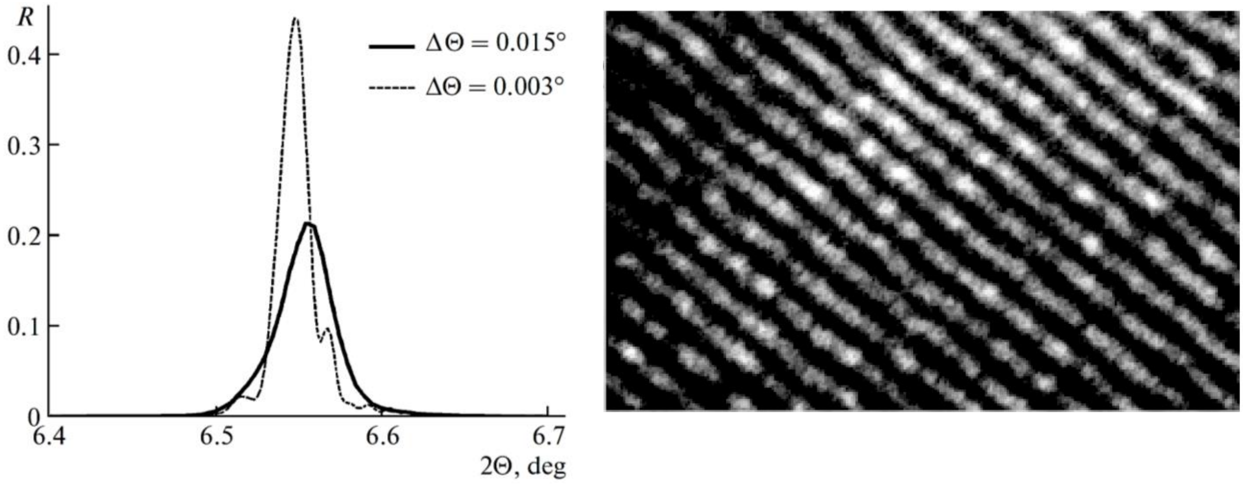


**(*a*)** Electron microscopy grid (rectangular openings of ~50 μm). **(*b*)** SEM image of exposed photoresist SU-8 using WC/Si ML mask with a pattern of (*a*). The pattern shrinkage is ~14; θ= 4°; λ~0.35 nm; the mask-photoresist distance is ~40 mm. General view shows 4 periods in horizontal direction. **(*c*)** An enlarged image of the imprint part from (*b*). The measurements are made at the MAX II synchrotron (Lund, Sweden).

**Reference:** V.S. Chumak, S. Peredkov et al. “Reflective X-ray masks for X-ray lithography”, J. Micromech. Microeng. v. 34, 045008 (10pp) (2024).

# High-resolution multilayer X-ray mirrors

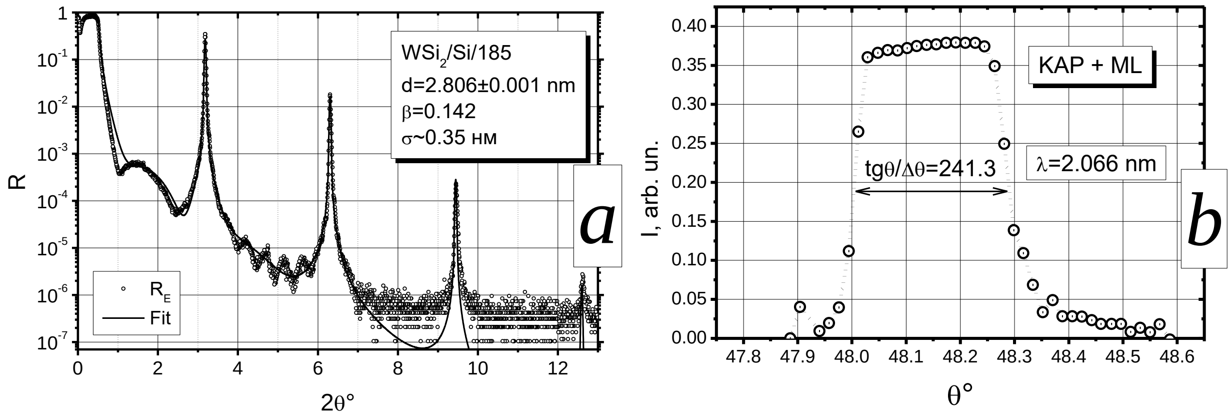
**ML:** W/B4C; period $d=t_W+t_{B4C}=1.35$ nm; $\beta=t_W/d\sim0.4$; $\lambda=0.154$ nm; $\lambda/\Delta\lambda\sim200$.



Reflectance of the 1st diffraction maximum for a W/B4C ML (d=1.35 nm) recorded with Cu$K\alpha_1$ radiation ($\lambda=0.154$ nm) at an incident beam divergence ($\Delta\theta$) of 0.015° and 0.003° (left). Cross-sectional TEM view of a 1.35-nm W/B4C ML (right).

**Reference:** I.A. Kopylets, V.V. Kondratenko, E.N. Zubarev, and D.V. Roshchupkin, "Formation of short-period multilayer W/B$_4$C compositions", Technical Physics, v. 57, No. 12, pp. 1709–1715 (2012).

**ML:** W/Si; period $d=t_W+t_{Si}\approx2.81$ nm; $\beta=t_W/d\sim0.14$; $\lambda\sim2.1$ nm; $\lambda/\Delta\lambda\sim240$.



**(a)** Measured small-angle X-ray reflectogram (circles) and fitting curve (line) for W/Si ML with thin W-layers ($\lambda=$**0.154** nm). **(b)** Reflection curve of W/Si ML (period d~2.8 nm) at ω-scan with synchrotron radiation ($\lambda=$**2.066** nm) using organic KAP crystal as a monochromator.

**Reference:** Y.P. Pershyn, A.Yu. Devizenko, V.V. Kondratenko, H. Modrow, F.-J. Hormes, "Structural and X-ray optical characteristics of W/Si multilayer X-ray mirrors," Metallofiz. Noveishie Tekhnol., v. 38, No. 3, p. 367-388 (2016).

# Thank you
# for your attention