Reflectance and resolution of multilayer monochromators for photon energies from 400 – 6000 eV

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Abstract. This paper deals with multilayer monochromators for synchrotron beamlines that are produced by magnetron and ion beam sputter deposition (MSD and IBSD). Different material combinations (W/B_4C, W/Si, Mo/B_4C, Mo/Si) with period thicknesses between 1 nm and 10 nm have been fabricated and measured at the synchrotron BESSY II (optics and KMC1 beamlines). The main challenge for the deposition of nanometer multilayers is to find growth conditions where the interfaces between adjacent layers are abrupt (no interdiffusion σ_d) and smooth (no roughness σ_r). The interface width σ ($\sigma^2 = \sigma_d^2 + \sigma_r^2$) becomes increasingly important for smaller period thicknesses. One decisive point for the interface formation is the kinetic energy distribution of the particles arriving on the substrate surface. In MSD, the sputter gas pressure is the main parameter for influencing the kinetic energy of the particles. In IBSD, an assist ion beam source can be used to bombard the growing film with inert gas atoms of a specific energy. Using this option, the best compromise between low interdiffusion and low roughness can be found for every material combination. Investigations of the reflection of W/B_4C multilayers with period thicknesses of 1.2 nm and number of periods N = 50, 300 and 600 show that no roughness increase occurs with increasing N. Typical values for the interface widths are σ = 0.27…0.28 nm.

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INTRODUCTION

The advantages of nanometer multilayers for the application as collimators, monochromators or polarizers in synchrotron beamlines are (1) high reflectances, (2) the possibility to design the multilayer for a needed spectral bandwidth and (3) the fact that higher reflection orders can specifically be suppressed. Because of the existence of numerous absorption edges in the photon energy region between 400 and 6000 eV it is impossible to find one multilayer system that exhibits optimal performance over the entire spectral range. Typical materials we apply for this energy range are W/Si, W/B_4C, Mo/Si, Mo/B_4C, Ni/BN, Cr/Sc, Cr/C, La/B_4C. In this paper we will focus on the W and Mo based systems, because they can be used in the broadest energy range. The other multilayers are rather singular solutions for specific energies (e.g. for oxygen emission line, water window, carbon or boron emission line).

MULTILAYER FABRICATION

Nanometer multilayers with single layer thicknesses in the range between 0.5 nm and 20 nm are synthesized using ultra-high vacuum thin film deposition techniques, like sputtering or pulse laser deposition (PLD). Typical values obtained with magnetron sputter deposition (MSD) and ion beam sputter deposition (IBSD) are:

- Layer thickness uniformity: ≥ 99.9 %
- Run-to-run reproducibility: 99.8 – 99.9 %
- Layer micro-roughness σ_r (rms): 0.15 – 0.25 nm
- Multilayer interface width σ (rms): 0.25 – 0.35 nm

Additionally to the MSD which already has been described elsewhere [1], since 2005 we have the option to use IBSD, which offers a higher flexibility concerning the independent choice of relevant deposition parameters like particle energy and particle flux density. Furthermore, the availability of a secondary assist ion beam pointing to the substrate surface enables a well-controlled activation of surface diffusion resulting in smoother films (figure 1).

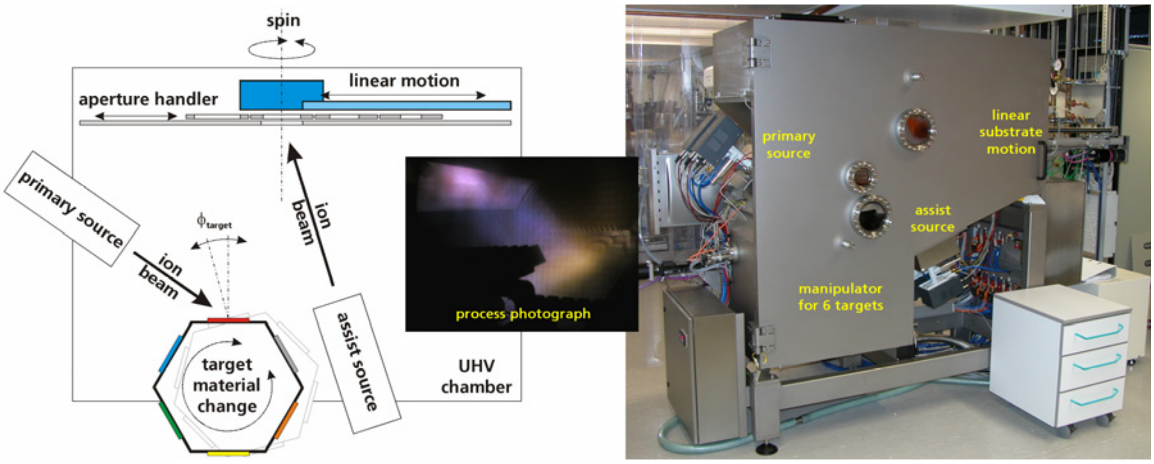


FIGURE 1. Front view of the principle of the large-area IBSD machine developed by the company Roth&Rau Wüstenbrand and IWS Dresden. The chamber is equipped with two linear ECR (electron cyclotron resonance) ion beam sources of 400 mm length. Substrates with diameters of up to 200 mm can be handled via the load-lock at the backside of the deposition chamber. Larger substrates with lengths of up to 500 mm or diameters of up to 450 mm have to be introduced via the front door.

MULTILAYER CHARACTERIZATION AT BESSY II

Multilayer Interfaces

Nanometer multilayers act as BRAGG reflectors for X-rays. Hence the performance of the multilayers is strongly determined by the interface characteristics. Considering the interfaces of multilayers, two phenomena can not be completely avoided: interface roughness and interdiffusion (figure 1).

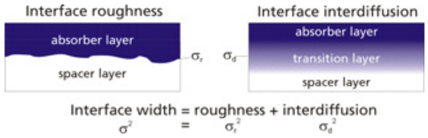
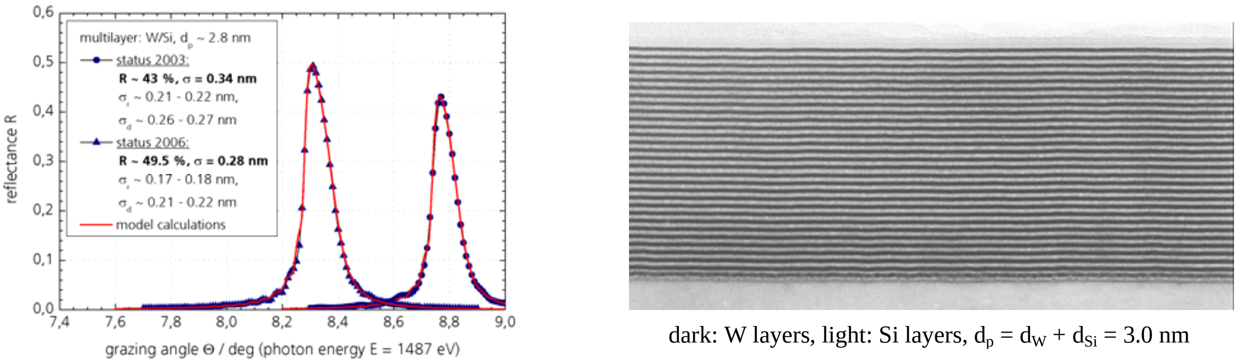


FIGURE 2. Schematic representation of typical nanometer multilayer imperfections: roughness and interdiffusion. Both effects result in reductions of the optimal optical performance.

In the past, a lot of effort has been directed to the reduction of interface widths of different multilayer systems, like W/Si, W/B_4C, Mo/Si, Mo/B_4C, Cr/C, Ni/C, La/B_4C and Cr/Sc. As an example the progress made for W/Si is shown in figure 3.



dark: W layers, light: Si layers, $d_p = d_W + d_{Si} = 3.0$ nm

FIGURE 3. Left hand side: Reflectance of W/Si multilayers in different development states. Currently interface widths of $\sigma = 0.28$ nm (rms roughness $\sigma_r = 0.17 - 0.18$ nm, rms interdiffusion $\sigma_d = 0.21 - 0.22$ nm) can be obtained on highly-polished silicon wafer substrates. Right hand side: High-resolution TEM micrograph showing smooth and chemically abrupt interfaces.

Reflectance and Resolving Power

In order to quantify the values of reflectance and resolving power of real nanometer structures we fabricated multilayers with different materials and period thicknesses. The measurements of the reflectance spectra were performed at two different BESSY II beamlines: For the energy range E = 400 – 1800 eV measurements were carried out at the “Optics beamline”, the measurements for energies E = 1800 – 6000 eV were made at the “KMC 1 beamline” [2]. The results obtained are shown in figures 4 and 5.

It turns out that by changing the multilayer parameters (materials, period thickness, ratio between absorber and spacer layer thickness, number of periods) a reasonable compromise between the demands for high reflectance and high resolving powers can be found. With multilayers developed for second-order suppression a slightly decreased reflectance compared to the reflectance optimized multilayers has to be taken into account.

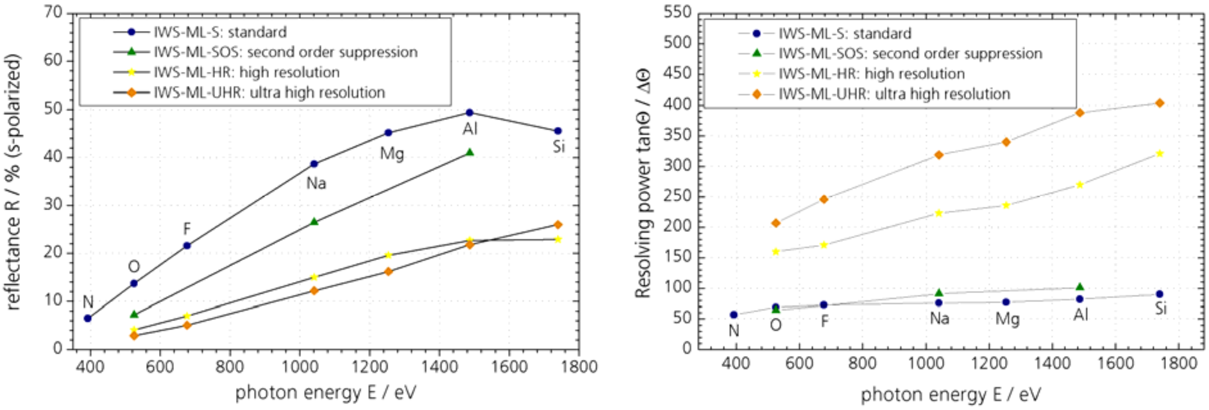


FIGURE 4. Left hand side: Reflectance of different multilayer monochromator types in the energy range E = 400 – 1800 eV. Right hand side: Resolving power of different multilayer monochromator types. Outstanding resolving powers > 300 are possible for E > 1000 eV.

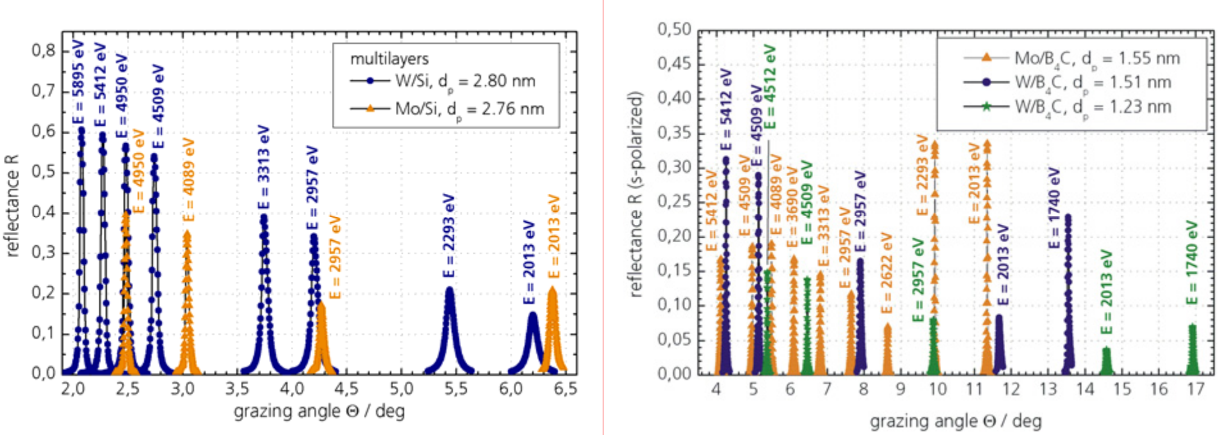


FIGURE 5. Reflectance spectra of different multilayer monochromator types in the energy range E = 1800 – 6000 eV.

Multilayers as X-Ray Polarization Analyzers

Many X-ray experiments require the knowledge of the polarization state of the radiation. Particularly for investigations of magnetic properties, the degree of polarisztion is the normalization factor for the degree of the magnetic effects (e. g. magnetic linear dichroism, magnetic circular dichroism). Multilayers can be used as linear analyzers around the Fe and Ni 2p edges, respectively. The working angle is the Brewster angle at which the polarizing power $(R_s\text{-}R_p)/(R_s+R_p)$ has a maximum. Polarization measurements are done by azimuthal rotation of the multilayer optic around the light axis [3].

The challange arising from the intention to use multilayers as analyzers for photon energies of E = 710 eV (Fe 2p edge) and E = 850 eV (Ni 2p edge) is that the period thicknesses of the multilayers have to be extremely small: d_p = 1.23 nm and d_p = 1.03 nm. In order to get reasonable reflectance values R, high numbers of periods have to be coated with an outstanding regularity and the interface widths σ have to be as small as possible. Considering the influence of σ on R, a dramatic decrease of R with increasing σ has to be taken into account (figure 6, left hand side). However, we could show that at least the interface width does not increase with increasing numbers of periods N. In fact, we rather observe a slight reduction of the interface width for larger N values which is attributed to a smoothing of layer roughness in the course of the deposition process (figure 6, right hand side).

The reflectance values measured at BESSY II are for E = 710 eV: R = 0.49 % (N = 50), R = 4.3 % (N = 300), R = 5.2 % (N = 600) and for E = 850 eV: R = 0.4 % (N = 150). The polarization power $(R_s-R_p)/(R_s+R_p)$ measured using E = 710 eV is better than 96.5 % (figure 7).

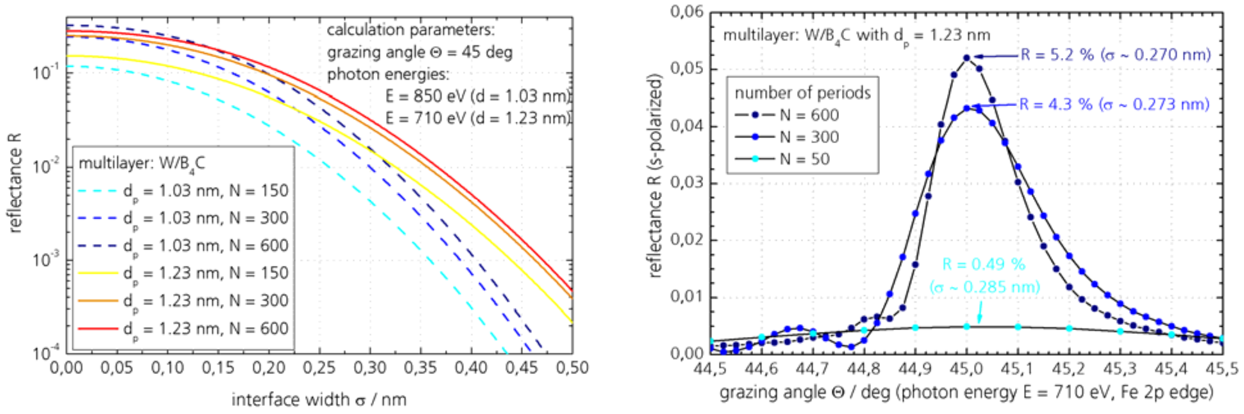


FIGURE 6. Left hand side: Influence of the interface width σ on the reflectance R for W/B_4C analyzers for E = 710 eV and E = 850 eV with period thicknesses of d_p = 1.23 nm and d_p = 1.03 nm, resp. (model calculations). Right hand side: Reflectance measurements of W/B_4C multilayers with d_p = 1.23 nm and different numbers of periods N. With increasing N the interface widths σ slightly decrease.

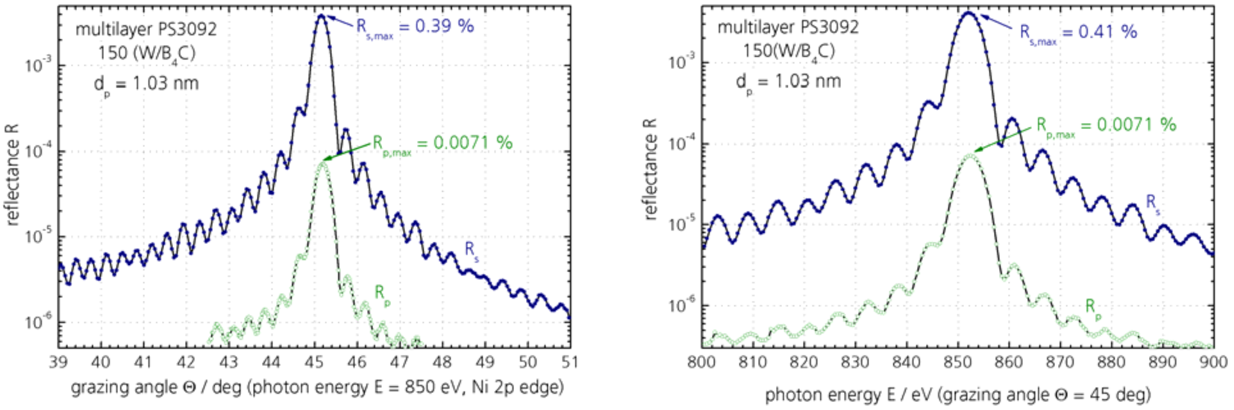


FIGURE 7. Left hand side: Θ-2Θ scans with s- and p-polarized light of a W/B_4C multilayer with d_p = 1.03 nm at E = 850 eV. Right hand side: Energy scans with s- and p-polarized light of a W/B_4C multilayer with d_p = 1.03 nm at E = 850 eV. The polarizing power $(R_s-R_p)/(R_s+R_p)$ is better than 0.965.

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