W/B short period multilayer structures for soft X-rays

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Abstract

X-ray W/B multilayer mirrors with a period of 2.5 nm were deposited by dc magnetron sputtering and studied in a comparison with W/Si multilayer systems of the same period. TEM, GIXR, and XPS analysis revealed that the layer quality and interfaces of the W/B multilayers are not better than the W/Si multilayers. Strong intermixing between W and B is present, which leads to compound formation with little or no pure W left after the interaction: an optically unfavorable boride formation and an increased roughness result in a reduced reflectivity. The deposited W/B multilayer mirrors showed a reflectivity of 34.5% at 0.84 nm and angle of incidence 9.7° compared to 40% obtained for W/Si multilayers. Ion polishing applied on the boron layers did not result in improvements of the reflectivity.

1. Introduction

Multilayer X-ray mirrors working in the range Al Ka – O Ka (0.84 - 2.4 nm) are used in x-ray fluorescent spectroscopy (XRF) as analyzing monochromators at the grazing angles of incidence in the range from 9.7° to 29°. An advantage of using multilayer systems is the possibility to tune their period for a specific wavelength. High reflectivity is required as it allows for a higher sensitivity of XRF. Several multilayer systems, W/Si, W/B4C, W/C, and W/B are promising systems as they have theoretically high optical contrasts, hence high reflectivity in the range 0.84 - 2.4 nm. Shorter period multilayers would allow achieving higher resolution in XRF applications because they would allow obtaining a larger angular distance between the measured peaks corresponding to different elements. However, for the shorter periods, lower reflectivity is achieved in practice. As such, the period range 2 to 3 nm can be considered to be optimal to achieve acceptable resolution and reflectivity. However, limited literature is available on these multilayer systems for the discussed wavelength range.

Most of these multilayer mirrors were studied thoroughly for other applications [1–10]. Gan et al. [1] studied W/C in the period range 1.5 to 4 nm. According to that, good quality periodic systems could be obtained when the W layers were thicker than 0.75 nm. Thinner W layers were found to show island-like growth, worsening the quality of the interfaces. In comparison, studies on W/B4C showed a better periodicity and higher reflectivity than W/C [6,8,10,11]. However, it was reported that W-B4C interaction leads to a W₅Cₓ compound formation and an increase of thickness errors which negatively affected the reflectivity and quality of the multilayer mirrors. All systems, W/C, W/B4C, and W/Si were found to have a decreased density of the reflector layers as a result of a chemical interaction between the spacer and the metal layer, for thicknesses of the W layer less than 0.75nm. As such, the optical contrast of the multilayer mirrors was lower than theoretically expected, limiting the reflectivity. However, no measurements of the reflectivity in the soft x-ray range were done for those multilayer systems, except for W/Si. Therefore, we took the W/Si system from our previous research, as a reference for our studies [3]. So far the highest reported reflectivity (40%) was achieved for W/Si at 0.84 nm which is 20 abs. % lower than the theoretical value for a W/Si multilayer mirror without any interfacial roughness (σ = 0). The main reason for the reduced reflectivity was an interaction between W and Si which led to a tungsten silicide formation and an interfacial roughness which could not be reduced further.

In this work, we synthesized and analyzed short-period W/B multilayer systems that to our knowledge have not been experimentally studied before. Theoretically, i.e. when taking again σ = 0, W/B shows the highest reflectivity, 62.6% at 0.84nm, compared to about 60% for W/Si, W/B4C, and W/C systems. The purpose was to study the interaction between the layers in the system and determine if a higher optical contrast between the layers could be obtained in comparison to a reference W/Si multilayer.
2. Experiment

2.1 Multilayer deposition

All multilayer mirrors were deposited on super-polished silicon wafers 25mm x 25mm (RMS roughness ~0.14nm) using DC magnetron sputtering system with a base pressure of 1x10^-9 mbar. Ar was used as a working gas at the pressure of about 1x10^-3 mbar. Depositions were performed at the power of 84W for W and 575W for B, with the areas of the targets being 78.5cm². W was deposited with lower power in order to have better control of thickness. The deposition rates were 0.05nm/s and 0.031nm/s for B and W, respectively. A 15cm DC Kaufman-type ion source (Veeco Instruments) with a molybdenum three-grid lensing system was used for the experiments. The ion source was operated at Ar flow of 5 sccm, with the energy of extracted ions being 100eV, and the current density of the ions on the substrate being 566µA/cm². The ion gun was mounted at 60 degrees grazing to the substrate at a distance of 70cm.

The multilayer mirrors consisted of 200 periods with a period of 2.5 nm and gamma values (Γ=d_W/d_W+d_B) varying from 0.08 to 0.36. To avoid uncontrolled oxidation of the surfaces after exposure to the air, every mirror was finished with a B layer of the same thickness as in the stack. The substrate holder was rotating at 60rpm during the deposition process. The schematic configuration of the chamber is illustrated in the Fig.1.

Fig.1: Configuration of the deposition setup. The spinning substrate is fixed in the middle of the deposition chamber 30 cm above the magnetrons. The magnetrons move to the center of the chamber before the deposition of the layer and back once the deposition of the layer is finished. An ion source is mounted at 60 degrees with respect to the substrate.

2.2 Multilayer characterization

The multilayer mirrors were characterized by 0-2θ grazing incidence reflectivity measurement at CuKa wavelength (λ=0.154nm) using a Malvern Panalytical Empyrean diffractometer. Fast measurements for period thickness determination were performed with a hybrid monochromator consisting of a combination of an X-ray mirror and a 2-crystal Ge(220) 2-bounce monochromator. Longer measurements for structural reconstruction were performed with a 4-bounce Ge(220) monochromator to achieve the highest angular resolution. For the reconstruction we used a model-independent approach described in [12], where the multilayer period is segmented into multiple sublayers that can be adjusted semi-independently. This allows for a more versatile representation of structural profiles in comparison to rigid models, i.e. without sub-layer division, which is important for working with strongly intermixed films.

To measure the top surface roughness of the samples, a Bruker Dimension Edge™ Atomic Force Microscope (AFM) was used. A high-resolution tip Hi’Res-C14/Cr-Au by MikroMasch was used (radius of the tip was ~1nm).

For a qualitative assessment of interfacial roughness in the multilayer systems X-ray diffused scattering rocking curves were measured with a conventional X-ray tube at the wavelength of 0.154nm, with the procedure of the measurement being described elsewhere [13]. It is common to measure diffuse scattering at higher orders to observe a wider range of angles. However, due to the low intensity of the high order Bragg peaks, the scans in this work were performed at the second Bragg peaks.

The surface composition of the samples was determined by non-destructive X-ray Photoelectron Spectroscopy (XPS), using a Thermo Scientific Theta Probe Instrument employing monochromatic Al-Kα radiation. Base pressure in the XPS chamber was 5 x 10^-10 mbar.

Cross-sectional transmission electron microscope images of the multilayers were obtained with Philips CM30T instrument used in a bright field mode at 300kV with a point resolution of 0.2nm and line resolution of 0.14nm. All samples were prepared by mechanical polishing (Dimple Grinding/Polishing) followed by argon ion thinning at 600eV. The minimal thickness of the samples was 250nm.

Soft X-Ray reflectivity at 0.84nm and grazing angle of incidence of 9.7° was measured at the storage ring BESSY II at Physikalisch-Technische Bundesanstalt (PTB) in Berlin-Adlershof, Germany [14]. Since the reflectivity was measured at a grazing incidence angle, a 0.5 mm exit slit on the monochromator was used in order to reduce the size of the beam footprint on a sample.
3. Results and discussions

3.1 Soft x-ray reflectivity

Previously, it was reported that in W/Si, W/B/C and W/C multilayer systems compound formation takes place, which has a significant influence on the formed thicknesses of the layers and thus the gamma values ($\Gamma = d_{\text{metal}} / d_{\text{metal}} + d_{\text{spacer}}$) of the formed stacks [3,4,10,13,15]. Therefore, in order to find the optimum gamma value resulting in the maximum reflectivity at 0.84nm, a series of multilayer mirrors in a range of gamma values from 0.06 to 0.36 was deposited. According to IMD simulations [16] the optimum $\Gamma$ for an ideal W/B multilayer system is 0.23 at which the maximum reflectivity of 62.6% at $\lambda = 0.84$nm and the angle of incidence 9.7° is achieved. Fig.2 shows the highest measured reflectivity of the deposited W/B ($\Gamma = 0.12$) together with the simulation of an ideal multilayer system (interfacial roughness $\sigma = 0$) at 9.7°.

![Fig.2: The measured and calculated reflectivity versus wavelength for the deposited W/B multilayer (blue line) and an ideal multilayer (no interfacial roughness, dashed line), correspondingly. The angle of incidence is 9.7°.](image)

Note that the highest measured reflectivity was obtained for $\Gamma = 0.12$, rather than $\Gamma = 0.23$ expected based on the calculations. This strong difference can be explained by the interactions taking place between layers that have a significant influence on the formed thicknesses of the layers. This effect was previously observed for W/Si systems as well [3]. As it can be seen from Fig.2 the maximum reflectivity at 0.84nm is $R = 34.5\%$ which is 28 % (absolute value) lower than the theoretical value for an ideal multilayer system, and 5.5% (absolute value) lower than the reflectivity of W/Si reported previously [3]. The reflectivity data at 0.84nm and angle of incidence 9.7° for all the deposited W/B multilayer systems is provided in the Table 1.

<table>
<thead>
<tr>
<th>Gamma value</th>
<th>Reflectivity at 0.84nm</th>
</tr>
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<tbody>
<tr>
<td>0.06</td>
<td>22.21%</td>
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<tr>
<td>0.08</td>
<td>29.54%</td>
</tr>
<tr>
<td>0.12</td>
<td>34.5%</td>
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<tr>
<td>0.18</td>
<td>32.66%</td>
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Spiller et al [17] reported that implantation of Ar species in the Si layers could reduce reflectivity. The presence of Ar in the B layers could affect the reflectivity too. However, XPS analysis did not reveal the presence of Ar or any other contaminant in our samples. So the relatively low reflectivity of the W/B multilayers could not be explained by contamination. Other possible reasons could be roughness and/or interaction between the layers, which is addressed in the following sections.

3.2 Atomic force microscopy measurements

In order to verify the role of layer roughness, we did AFM measurements. The measurements were done both for W/B ($\Gamma = 0.12$, N=200) and W/Si ($\Gamma = 0.12$, N=200) multilayer systems to also be able to make a comparison between them. The measured absolute rms values for W/B and W/Si were 0.143 and 0.134 nm, respectively, which is at the limit of the AFM sensitivity. The probed area for both samples was 1x1μm. So no differences in roughness were determined within the resolution of AFM. Note that surface roughness can in some cases be affected by oxidation of the surface. Keeping in mind that the B and Si oxides may reconstruct or smoothen the surface, other methods of analysis to study the layer roughness were required.

3.3 Transmission electron microscopy

The interfaces were additionally analyzed by means of TEM. Fig.3 shows TEM images of W/B (left) and W/Si (right) multilayer structures with the following characteristics: $d=2.5$nm, N=200, and $\Gamma = 0.12$. Both multilayer systems seem to have relatively sharp interfaces. Another point evident from the TEM pictures, is that the as-deposited gamma value is significantly higher than the nominal gamma $\Gamma = 0.12$ in both systems. This substantial difference cannot be explained by errors in the calibration of thicknesses in the deposition process but should be associated with interactions between the layers. These interactions can considerably modify thicknesses of the deposited reflector and spacer layers e.g. via an intermixing process or compound formation. As a result, the optical index profile can substantially deviate
from the intended profile, which will affect the X-ray reflectivity of the structures. TEM did not reveal significant differences in the density profiles of the W/B and W/B multilayers as judged by the intensity modulation (Fig. 3b). However it is not possible to extract quantitative information from such measurements due to a difficulty to have a proper reference intensity level in TEM. To look into this further, this point has been addressed by GIXR described in the following section.

3.4 Model-independent analysis of GIXR

To obtain quantitative data on the interface and layer profiles for the investigated systems, GIXR analysis was applied. We used a model-independent method of structural reconstruction, described in detail elsewhere [12]. Our method assumes an ideal periodicity, which puts requirements on the period-to-period reproducibility of the multilayer samples. Thickness errors lead to the broadening of the Bragg peaks and/or splitting of them, which cannot be simulated in our layer reconstruction method. Accumulation of small instabilities in the deposition process [18] leads to a stronger peak broadening in the structures with larger number of periods. Furthermore, the larger the total thickness of the multilayer film, the larger the curvature of the sample due to the internal stress in the film. A strongly curved sample does not allow for accurate measurement of the total external reflection and can modify the critical angle. Note, that the W/B systems were found to have about a factor of four higher sample curvature than W/Si as checked by white light interferometry. For both of these reasons, the multilayer structures with 200 periods could not be used for GIXR analysis.

We, therefore, deposited an additional multilayer structure W/B, with d= 2.5 nm, Γ=0.12, and the number of periods N=50, and measured GIXR data. The reference multilayer system, W/Si with d=2.5nm, Γ=0.12 and N=50, was deposited and analyzed in our previous research [3]. Fig. 4a and b (red points) show the corresponding reflectivity curves of these systems. The model-independent approach was used to reconstruct the multilayer structure from these measurements. For fitting the GIXR curves from Fig. 4a and b, the periodic part of the multilayer mirrors was divided in 13 sublayers. The reconstruction started from a step-like profile and finished in about 200 iterations with the profiles shown in Fig.4c. As can be seen from Fig. 4a and b, the calculated GIXR curves fit well the experimental ones, with all the Bragg peaks fully described and the shape of the XRR curve in between the Bragg peaks mostly matching. The results of the reconstruction are shown as delta-profiles in Fig.4c where δ =1-Real(n), n – optical constant [12].

As seen, the shape of the reconstructed interface profiles in W/B and W/Si is almost identical, which is qualitatively in agreement with the TEM data. The only noticeable difference is the highest delta values. The tabulated delta value for pure W is 4.6 x 10^5 [19], whereas the highest delta values from the reconstructed profiles are only 2.7 x10^5 and 2.8 x 10^5 for W/B and W/Si systems, respectively. This means that there is no pure W present in any of the multilayer systems, with the difference in the highest delta values for the two systems being rather small. The maximum delta value for W/B corresponds to the tabulated value of W_2B_3 of 2.75 x10^5. The maximum delta value for W/Si comes close to the tabulated value of WSi_2 of 2.5 x10^5, although it does not match it exactly. This can be explained by a formation of a mixture of several compounds, e.g. two neighboring silicides found in the W-Si phase diagram, WSi_2, and W_3Si_2.
Thus, based on TEM and GIXR analysis, the W/B system did not prove to be structurally better than W/Si multilayer. This explains its relatively low reflectivity at 0.84 nm. In both systems, compounds are suggested to be formed due to strong intermixing. To check the formation of these compounds and the fact that no pure W is present in the multilayers we performed XPS measurement, which is described in the following section.

### 3.5 X-ray photoelectron spectroscopy measurements

GIXR analysis of W/B and W/Si multilayers (d= 2.5 nm, Γ=0.12) suggested there is no pure W present and indicated the formation of certain compounds in the structures. To check that, non-destructive XPS measurements were done on the surface of these multilayers. Taking into account 5-7 nm depth of information for XPS, the signal was obtained from about two top periods of the stacks. Fig.5 shows the signal from W 4f peaks, obtained for the multilayers and a reference W film that was sputter cleaned directly before the measurements. In order to facilitate comparison of the peaks, the intensity scale is normalized to the W4f 7/2 peak.

To our knowledge, there are no studies in literature that unambiguously relate the binding energy of the W4f peak to WBx composition. However, most literature results on tungsten-boron and tungsten-boron-carbon compounds indicate a positive change in binding energy between 0.3 and 0.8 for WBx compounds, relative to W metal [20–22]. This is consistent with a peak position of the W4f 7/2 peak at 31.5 eV binding energy observed here for W/B multilayers, compared to 31.1 eV for a W metal reference. Similarly, a shift of the W4f peak to lower binding energy (30.9 eV) upon silicide formation is in line with reported XPS studies on metal silicide formation for W/Si systems [23][24]. These differences in binding energy are small compared to the typical resolution achievable with laboratory XPS systems, which complicates the use of peak fitting to separate the formed WBx and WSix compounds and the fact that no pure W is present.

To check the formation of these compounds, relative to W metal [20–22]. This is consistent with a peak position of the W4f 7/2 peak at 31.5 eV binding energy observed here for W/B multilayers, compared to 31.1 eV for a W metal reference. Similarly, a shift of the W4f peak to lower binding energy (30.9 eV) upon silicide formation is in line with reported XPS studies on metal silicide formation for W/Si systems [23][24]. These differences in binding energy are small compared to the typical resolution achievable with laboratory XPS systems, which complicates the use of peak fitting to separate the formed WBx and WSix compounds and the fact that no pure W is present.

Similarly, a shift towards lower binding energies indicates a silicide formation; a shift towards higher binding energies indicates a boride formation.

The XPS results are thus in line with a negligibly small fraction of unreacted W metal, as concluded from GIXR data in both W/B and W/Si multilayer structures. The high density layers formed during the deposition are made of certain W compounds. However according to the reconstructed delta profiles from GIXR, the difference in the highest delta values at 0.154 nm for the two systems was rather small, and this did not explain why the reflectivity of the W/B multilayer was significantly (by 5.5 abs.%) lower than that of W/Si at 0.84 nm. To further look into that, we did model simulations at 0.84 nm wavelength which are described in the following section.

### 3.6 Model simulations at 0.84 nm wavelength

The delta profiles (shown in Fig. 4c) obtained from GIXR, indicated the formation of W$_3$B$_5$ instead of a pure W layer, suggesting the formation of W$_3$B$_5$/B instead of a W/B multilayer. Similarly, WSi$_x$/Si was formed instead of a W/Si
multilayer. We used this data to assess if such compositions of the multilayers could explain the experimental reflectivity obtained at 0.84 nm, by IMD model simulations.

We started our simulations with the WSi₂/Si system. A two-layer model WSi₂/Si with \(d=2.5\text{nm}, \Gamma=0.315\), and \(N=200\) was used to fit the reflectivity. The \(\Gamma=0.315\) was chosen based on the reconstructed delta profiles in Fig. 4c. The obtained maximum delta value for W/Si in Fig. 4c did not match the tabulated delta values of any of the pure silicides but was found in between the values of WSi₂ and WSi₃. So we used a mixture of these two silicides to match the obtained maximum delta value. As such an effective stoichiometry of \(x=1.28\) and a density of \(\rho=10.68\) was calculated and used for the reflectivity simulations. The roughness of the interfaces was taken into account by applying a Debye-Waller factor at each of the interfaces. The calculations showed that the 40% reflectivity (measured on the experimental multilayer) can be obtained for the modeled system with the Debye-Waller factor being \(\sigma=0.25\) nm. We used this as a reference for further calculations.

At the next step, we replaced WSi₂ with W₃B₃ in our simulations. A two-layer model W₃B₃/B was used, with \(d=2.5\text{nm}, \Gamma=0.315, N=200\), and Debye-Waller factor \(\sigma=0.25\) nm. The tabulated density \(\rho_{W2B5}=11\text{g/cm}^3\) was used. This calculation resulted in the reflectivity of 37.5%. So the W₃B₃ compound reduced reflectivity by 2.5 abs.% compared to the WSi₂ silicide used in the simulations above. The remaining 3 abs.% of 5.5 abs.% could be explained if we would increase the Debye-Waller factor from \(\sigma=0.25\) to \(\sigma=0.31\) nm. XPS depth-profile measurements revealed presence of oxygen in the top B layer, which is a result of the surface oxidation after the exposure of the structure to air. Oxygen was not found in the deeper layers. Therefore, we added a layer of boron oxide (B₂O₃) in our model with a thickness of 2 nm. The layer of B₂O₃ did not cause reduction in reflectivity by more than 0.5% at wavelength, therefore, we could conclude that oxidation of the top surface was not the reason for the strongly reduced reflectivity.

Fig. 6 shows the simulated and measured reflectivity for the W/B multilayer. As it can be seen the width of the simulated reflectivity peak is narrower than the one measured at 0.84nm. It could be explained by an accumulated effect of the thickness errors occurring during the deposition of the 200-period stack. Although such a peak cannot be uniquely fit, our simulations showed that such broadening can be caused by RMS random thickness error of the layers in the range 0.04 - 0.05 nm. However, our data obtained on the multilayers with a smaller number of periods do not support such a large thickness error. Based on GIXR we estimate the actual random thickness errors to be about a factor of three smaller. Alternatively, systematic period shift could explain the observed data. Unfortunately, there cannot be a unique solution found for the systematic period shift. However, we could estimate that in the worst case such period shift could result in about 3 abs.% reflectivity loss.

Fig. 6: The simulated reflectivity of W/B multilayers at an angle of incidence of 9.7°, compared to the highest measured reflectivity of a W/B multilayer (N=200, d=2.5 nm, \(\Gamma=0.12\)). Parameters used for the simulation: two layer W₃B₃/B model, N=200, d=2.5nm, \(\Gamma=0.315, \sigma=0.312\)nm.

Thus, the model simulations showed that the reduced reflection of W/B with respect to W/Si at 0.84nm can be explained by a combination of several factors: formation of a compound unfavorable for 0.84 nm wavelength, higher interfacial roughness, and somewhat larger layer thickness errors. But TEM and AFM did not reveal any differences in the roughness of the two systems. To verify this further, we performed diffuse scatter measurements that have a very high sensitivity to roughness in multilayers.

3.7 Diffuse scatter measurements and ion polishing

To compare interfacial roughness in the W/B and W/Si multilayers, X-ray diffuse scattering at CuKα wavelength (\(\lambda=0.154\text{nm}\)) was measured by mean of the rocking curve scan. The measurement was done by rocking the sample around a second Bragg position \(\theta=3.48°\) in a wide angular range, with the detector being fixing at \(2\theta=6.96°\) (Fig.7).

Fig.7: Rocking curve scans for W/B (d=2.5nm, N=200, \(\Gamma=0.12\)) and W/Si (d=2.5nm, N=200, \(\Gamma=0.12\)) around the position of the second Bragg peak \(\theta=3.48°\) and detector a \(2\theta=6.96°\).

Although we were not able to extract quantitative data from these measurements, the higher diffuse scattering from W/B in the entire angular range is qualitatively in agreement with the model simulation (section 3.6) that suggested a higher interfacial roughness in W/B compared to W/Si.
As it was reported [15,25–27], ion polishing is an effective tool to reduce interfacial roughness in some of the multilayer systems and hence improve reflectivity. To test this possibility for W/B multilayers, we performed an experiment where every B layer was polished with 100eV Ar+ ions, with an etched thickness of 0.3 nm. The energy of 100eV was selected as it is high enough to initiate mobility of the surface atoms but not too high to cause ballistic intermixing with the underlying layer. To compare interfacial roughness in the polished and unpolished structures, X-ray diffuse scattering at CuKa wavelength ($\lambda=0.154\text{nm}$) was measured by mean of the rocking curve scan, shown in Fig. 8.

Fig.8: Rocking curve scants for the W/B ($d=2.5\text{nm}, N=200, \Gamma=0.12$) multilayers with (blue line) and W/B ($d=2.5\text{nm}, N=200, \Gamma=0.12$) without (red line) ion polishing of B layers. The polishing was done with 100eV Ar+ ions, with the etched thickness of 0.3 nm.

A substantial reduction in diffuse scattering is observed after applying the ion-polishing, which usually implies a reduction of roughness. However, the measured reflectivity of the ion-polished multilayer did not result in any reflectivity changes at 0.84 nm wavelength – both unpolished and polished multilayer systems showed reflectivity of about 34.5% at 0.84 nm. A similar effect was observed in our previous work on the W/Si systems where a substantial decrease of diffuse scattering was caused by a strong reduction in the vertical correlation length of roughness, but insignificant changes in the amplitude of roughness [3]. We presume that the same effect is also observed in the ion-polished W/B multilayers. Nevertheless, it cannot be excluded that other parameters can be found, including the ion species, ion energy, and the amount of etched material, which will still allow further reduction of roughness in W/B multilayers.

4. Conclusions

We have synthesized and analyzed 2.5 nm period W/B multilayer X-ray mirrors and compared these with more established 2.5 nm period W/Si mirrors. The main goal was to study the interaction between the layers in the system and determine if a higher optical contrast between the layers could be obtained in comparison to reference W/Si multilayers. However, the deposited W/B multilayers mirrors showed a reduced reflectivity of 34.5% at 0.84 nm compared to 40% obtained for W/Si multilayers.

Based on TEM, GIXR, and XPS analysis, the W/B multilayers did not prove to be structurally better than W/Si multilayers. We have identified strong intermixing between W and B leading to a compound formation, with little or no pure W left after the interaction. A similar process occurs in W/Si multilayers, although the reflectivity of W/B multilayers is lower than that of W/Si multilayers by about 5.5 abs.%. This is mainly because of optically unfavorable boride formation and a slightly increased roughness. Ion polishing of boron layers resulted in a significant reduction in the diffuse scattering of the W/B multilayer at 0.154 nm wavelength, but did not improve its reflectivity at 0.84 nm.

5. Acknowledgments

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References


Normalized intensity

\[ \theta, \text{deg.} \]

- W/B
- W/Si
Normalized intensity

$\theta$, deg.

- W/B unpolished
- W/B polished