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Multilayer X-ray mirrors Mo–B_4C — new crystals-analyzers for wavelength range of 5 to 12 Å

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Structure and X-ray optical properties of Mo–B_4C multilayer mirrors with period from 13.2 to 33.8 Å have been studied. The reflectivity values for the Mo–B_4C mirrors and the traditionally applied RbAP crystal ($2d$ = 26.5 Å) have been measured in the 4.7 to 11.9 Å range. The interlayer boundary roughness attaining 3 Å was found to be the main structure cause of the reflectivity drop with decreasing mirror period. The Mo–B_4C multilayer X-ray mirrors have been shown to provide 2 to 5 times intensity gain as compared to RbAP ones and to be the promising broadband diffraction elements.

Изучена структура и рентгенооптические характеристики многослойных зеркал Mo–B_4C с периодом от 13,2 до 33,8 Å. Измерены коэффициенты отражения в диапазоне длин волн 4,7÷11.9 Å для зеркал Mo–B_4C и традиционно применяемого кристалла RbAP ($2d$ = 26,5 Å). Установлено, что основной структурной причиной снижения коэффициента отражения с уменьшением периода зеркала является шероховатость межслоевых границ, достигающая 3 Å. Показано, что многослойные рентгеновские зеркала Mo–B_4C обеспечивают 2÷5-кратный выигрыш в интенсивности по сравнению с RbAP и являются перспективными широкополосными дифракционными элементами.

Due to high reflectivity and stability of properties, the multilayer X-ray mirrors have been used extensively in X-ray spectral analysis as the crystals-analyzers in the wavelength range from 18 to 200 Å [1]. Usually, in this range the mirrors with period H more than 35 Å are used, which, provide much higher reflectivity values than other known monochromators at good spectral resolution. However, application of the multilayer mirrors for a harder radiation of λ = 5 to 12 Å, to which the K-series of the 3rd Period elements are attributed, requires decreasing the layer thickness down to 5–15 Å to provide a satisfactory spectral resolution. Such layer thickness decrease is associated with fundamental technologic difficulties and is accompanied by a drastic reflectivity drop [2], thus, the multilayer mirrors may yield to the traditionally used crystals-analyzers RbAP, KAP, etc.

There are two reasons for the reflectivity drop. The first is caused by interlayer boundary roughness σ and results in the reflectivity drop with decreasing period H according to an approximate law $R \sim R_0 \exp[(-2\pi n\sigma/H)^2]$, where n is the reflection order. The second cause is associated with decreasing refraction index variation amplitude through the multilayer mirror depth as a result of the layer intermixing. Model calculations using the IMD software [3] show that the roughness, first of all, extinguishes the high-order harmonics in the angular dependence of X-ray reflectivity, while the layer intermixing suppresses all the harmonics almost similarly. The aim of the work is experimental efficiency test-

Table. The parameters of multilayer X-ray mirrors Mo–B_4C. The calculated molybdenum fraction in the period is 0.46

No.	Period, Å	Period amount
1	33.78	165
2	29.22	200
3	23.96	250
4	19.72	300
5	17.1	350
6	13.22	450

ing of short-period Mo–B_4C mirrors in the wavelength range of 4.7 to 11.9 Å and revealing the structure cause for the reflectivity decrease thereof.

The multilayer mirrors were deposited by dc magnetron sputtering in argon atmosphere. The substrate was alternatively exposed to the magnetron sources sputtering Mo and B_4C using a rotary mechanism in the vacuum chamber. The layer thickness reproducibility within 0.1 % was provided using sputtering rate stabilization and exposure time control. The argon working pressure was $1.5 \cdot 10^{-3}$ Torr; Mo deposition rate, 1.7 Å/s; that of boron carbide, 2.4 Å/s. The substrates were planar glasses with root mean square roughness 4 Å. The parameters of the mirrors are given in Table. The multilayer mirror period was determined from the positions of several diffraction maxima in small-angle diffraction patterns taking the refraction into account [1]. The measurements were done using a DRON-3M apparatus in Cu–$K_{\alpha 1}$ radiation obtained with Si (220) monochromator in the primary beam. For the wavelength range of 4.71 to 1.9 Å, the measurements were carried out using a SPRUT-V spectrometer (Ukraine) in the emission of analytical fluorescence lines of different materials. The fluorescence was excited by the spectrum of a shot-through BS-11 tube with Ag target, at 10 kV. The primary beam was registered by a flow-proportional detector with thresholds tuned for transmission of the selected analytical line. The scattered radiation contribution to the measured primary beam intensity was controlled using the scattering background of substances consisting of light elements (Be, B, C, O etc.), and did not exceed 3 %. The peak intensities from the crystals were measured at the same thresholds as for the primary beam measurements. The peak reflectivity

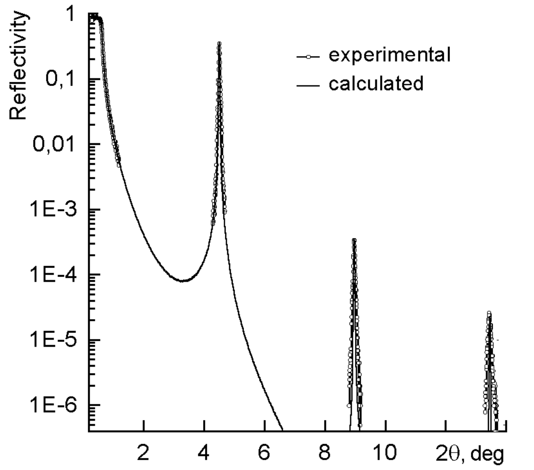

Fig. 1. A small-angle X-ray diffraction pattern for the Mo–B_4C multilayer with H = 19.72 Å period. Solid line shows the calculation by IMD program [3].

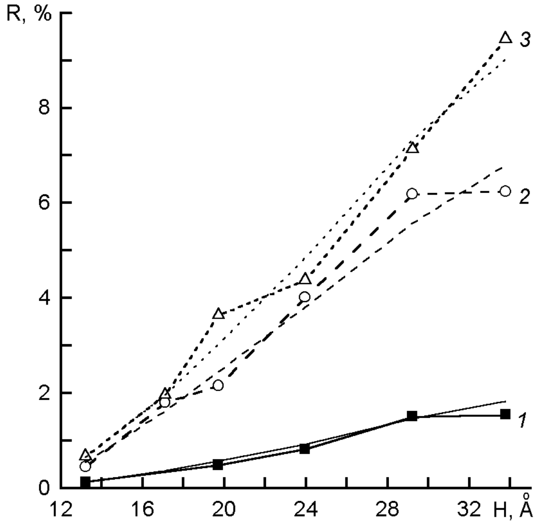

Fig. 2. Mo–B_4C mirror reflectivity vs the period value for different X-ray wavelengths: *1*, 4.73 Å (Cl–Kα); *2*, 5.37 Å (S–Kα); *3*, 9.89 Å (Mg–Kα), the lines without symbols, the calculation results.

was determined by the ratio of the reflected signal to the incident beam taking into account the correction for the scattered radiation background.

In the small-angle diffraction patterns of the multilayer X-ray mirrors with the period H from 13.2 to 33.7 Å, two to six Bragg reflections from the periodical structure can be observed (Fig. 1). The halfwidth of the peaks is practically independent of the reflection order, that indicates the constant structure period through the volume irradiated. An exception is the

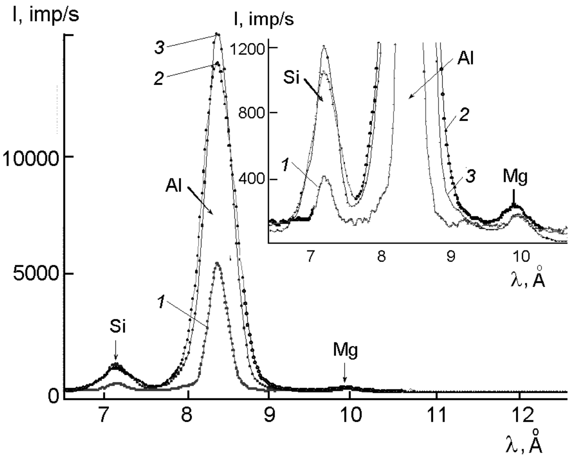

Fig. 3. Fragments of X-ray spectrum of AK5M2 aluminum alloy measured using different crystals-analyzers: RbAP (*1*); Mo–B_4C multilayer mirror, $H = 17.1$ Å (*2*); Mo–B_4C multilayer mirror, $H = 29.2$ Å (*3*).

sample with $H = 23.96$ Å, in which some blurring of the high order peaks is observed. Fitting of the calculated and the experimental patterns using IMD software [3] has established almost the same interlayer roughness $\sigma \approx 2.9$ Å for all the mirrors. As it was expected, the measurements in soft radiations showed the reflectivity drop by a factor of 12–15 as the mirror period decreased from 33.7 to 13.2 Å (Fig. 2). The curves calculated under assumption of invariable layer composition, density, and thickness ratio with decreasing the period H fit well the experimental ones at the interlayer roughness $\sigma = 3$ Å. Thus, the reflectivity drop with decreasing period of the Mo–B_4C mirrors is caused, first of all, by the roughness of interlayer boundaries.

The short-period Mo–B_4C mirrors with $H > 17$ Å provide a substantial gain in the spectral line intensity as compared to RbAP (Fig. 3). The spectra are of acceptable quality with reliable separation of silicon, aluminum, and magnesium lines. For practical application in scanning devices, the H range from 24 to 29 Å is optimal. However, in this case, one has to narrow the angular beam divergence in the X-ray optical scheme in order to improve the spectral resolution. Fig. 3 shows that with a proper collimation it is possible to obtain the higher quality spectra with higher intensity and better spectral resolution using the mirror with $H = 29.2$ Å than with $H = 17.1$ Å.

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Багатошарові рентгенівські дзеркала Mo–B_4C — нові кристали-аналізатори для діапазону довжин хвиль 5÷12 Å

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Вивчено структуру та рентгенооптичні характеристики багатошарових дзеркал Mo–B_4C з періодом від 13,2 до 33,8 Å. Проведено вимірювання коефіцієнтів відбиття у діапазоні довжин хвиль 4,7÷11,9 Å для дзеркал Mo–B_4C та кристала RbAP ($2d$=26,5 Å), який традиційно застосовується. Встановлено, що головною структурною причиною зниження коефіцієнта відбиття зі зменшенням періоду дзеркала є шорсткість міжшарових меж, яка досягає 3 Å. Показано, що багатошарові рентгенівські дзеркала Mo–B_4C забезпечують 2÷5-кратний виграш у інтенсивності у порівнянні з RbAP та є перспективними широкосмуговими дифракційними елементами.