08

Multilayer NiMo/C structures fabricated by reactive magnetron sputtering

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In this paper, the characteristics of a multilayer NiMo/C system, promising for Gebel-type mirrors, are investigated. The structures were synthesized by reactive magnetron sputtering in argon with pulsed nitrogen supply, the percentage of which in the chamber was equal to 15 % and 30 % of the total pressure of the working gas. The periods of multilayer structures 41.5 and 33.5 Å are calculated based on the actual systems of collimation and focusing of hard X-ray radiation in diffractometers of the DRON type (St. Petersburg). The effect of annealing at maximum temperatures of 250 °C and 320 °C on the reflective and structural properties of multilayer NiMo/C structures was studied. Based on the results of small-angle X-ray reflectometry at a wavelength of 0.154 nm, the structural parameters of NiMo/C were determined. It is shown that the values of the transition regions on the C and NiMo layers are in the range of 4−7 Å and generally tend to decrease or fluctuate slightly after annealing. After annealing, the NiMo/C samples synthesized with a nitrogen content of 15 % had reflection coefficients in the first order of 78.8 %−76.1 % for periods 41.5−33.5 Å respectively. For structures synthesized with 30 % nitrogen content, 81.4 %−77.4 %. The high reflectivity of the multilayer NiMo/C structures allowed us to assert that it is a good alternative to the Gebel-type mirrors based on a pair of W/Si materials widely used in technology.

Keywords: multilayer X-ray mirrors, reactive magnetron sputtering, Gebel type mirrors.

Introduction

The emergence of multilayer X-ray mirrors with a variable surface period [1,2] has significantly expanded the range of their applications. The production and improvement of the efficiency of collimating and focusing mirrors for the hard X-ray wavelength range have become important research areas [2–5]. We will talk about Gebel's parabolic mirrors in this paper. The use of such structures increased the radiation intensity by more than an order of magnitude in experiments on X-ray diffraction and small-angle scattering [5,6]. Today, many modern analytical instruments are equipped with such mirrors, for example, DRON and Bruker diffractometers [7]. Thus, the task of increasing the efficiency (reflectivity, among other things) of collimating and focusing optics for hard X-ray radiation remains relevant to this day.

Often in the world (including at the Institute of Physics of Microstructures of the Russian Academy of Sciences), W/Si is chosen as a pair of materials for Gebel mirrors [8–10]. Such mirrors have relatively high ($\geq 70\,\%$) average reflectances on the surface of the parabolic mirror at the operating wavelength $\lambda = 0.154$ nm (line emission Cu $K_{\alpha 1}$). However, it was experimentally demonstrated in Ref. [11] that quasi-Bragg scattering of the line Cu,Kβ with $\lambda = 0.139$ nm is manifested in W/Si multilayer structures. Non-specular reflection (quasi-Bragg scattering) was theoretically predicted in Ref. [12] and was previously experimentally observed in Ref. [13]. This is a consequence of the interference amplification of the intensity of scattered waves from the coherently repeating rough interfaces of the layers. In addition, the angular resolution of W/Si multilayer mirrors is quite low (the reflection peak is wide). Naturally, all this reduces the resolution of the diffractometer and can even lead to incorrect identification of peaks during X-ray diffraction analysis. Therefore, we are faced with the task of increasing the resolution and attenuating the side radiation line Cu Kβ.

The problems outlined above and ways to solve them were previously discussed in articles [7,10,14,15]. It was proposed to introduce a nickel filter into the X-ray optical system, which, compared with tungsten, has a higher absorption of Cu,Kβ-lines and a significantly higher transmission of Cu Kα-line. However, the use of an absorbing filter in the optical circuit leads to a decrease in the useful signal. At the same time, the complexity of the design of the X-ray optical system will increase — an additional element appears in it. Therefore, it is more logical to use the filtering properties of Ni directly in mirrors such as Ni/Si and Ni/C, which theoretically can have higher reflectivity and angular resolution compared to W/Si. This is shown, for example, in Ref. [14]. Thus, the use of nickel in the composition of a multilayer mirror can increase the ratio of radiation intensities $I_{\mathrm{Cu\,K}\alpha}/I_{\mathrm{Cu\,K}\beta}$ and solve the problem of suppression of the Cu Kβ-line. In addition, a higher reflectance can be expected from nickel-containing multilayer mirrors.

The structural and reflective characteristics of Ni/C and Ni/Si have been studied in detail in Ref. [16–20]. The authors studied the values of interlayer roughness according to reflectometry and transmission microscopy data, on the basis of which theoretical predictions of reflectances were carried out. The reflectivity of these mirrors was measured in the soft and hard regions of X-ray radiation. A low interlayer roughness ($\sigma \leq 0.3$ nm) and a high reflectance ($R > 75$ % at a wavelength of 0.154 nm) of the Ni/C structure with a period of $d \geq 3.5$ nm was reported in Ref. [20].

It should be noted here that nickel is a magnetic material. This circumstance significantly complicates the technological process of synthesis of Ni/C and Ni/Si mirrors by magnetron sputtering. As a rule, when working with targets made of magnetic materials, the target thickness is chosen to be less than 1 mm. Such thin targets quickly fail. This does not allow for long work cycles with them.

At the same time, an alloy of nickel with molybdenum at the level of 80% nickel and 20% molybdenum suppresses its magnetic properties [21], however, it retains almost completely the X-ray optical properties of Ni, as indicated by theoretical calculations. Thus, multilayer structures of NiMo/Si and NiMo/C can be chosen as an alternative to mirrors based on pure Ni.

We studied the reflective properties of NiMo/Si in Ref. [14]. Significant mixing of materials at the interface of the layers did not allow achieving high reflectivity. The peak reflectances in the first order at $\lambda = 0.154$ nm were within $R = 69.5\,\%-56.1\,\%$ for periods in the range of $d = 41.5-32$ Å. We proceeded to studying the structure of NiMo/C in Ref. [15]. The reflectances after annealing of the mirror were $R > 70$ % in the same range of periods, which was a great progress in solving the tasks set. At the same time, the theoretical limit for structures of this type lies in the region of about 90,%. Consequently, there remains the potential to increase the efficiency of the multilayer mirrors obtained in practice.

Existing methods for the synthesis of multilayer structures, in particular magnetron sputtering, do not allow achieving ideal interfaces. In practice, chemical interaction and diffusion of atoms reduce the optical contrast in a multilayer structure, and the development of interlayer roughness leads to diffuse scattering of radiation. The negative impact of both of these factors must be reduced, otherwise the X-ray mirror will not have a high reflectivity.

In the process of growing thin films, reactive sputtering in an active gas environment (most often nitrogen) is often used — a method that can effectively reduce mechanical stress, roughness and mixing in thin films. In some cases, nitrogen ions can occupy interstices in the unit cell of the sprayed particles and cause its distortion, which can lead to a nanocrystalline or amorphous structure of the deposited film [22]. For sputtered metal layers, the nanocrystalline or amorphous phase can lead to smoother interfaces of multilayer coatings due to the smaller grain size of crystallites or the absence of crystallites at all. A decrease in interface roughness and voltage was observed in the W/B_4C multilayer system manufactured by reactive magnetron sputtering in a mixture of argon and nitrogen gases [23].

On the other hand, due to nitriding and, consequently, passivation of the surface of the layers, mutual diffusion and the formation of compounds at the interfaces decrease, which was observed for several multilayer coatings (Cr/Sc [24], La/B [25,26], La/B_4C [27], Pd/Y [28]), including Ni/C [29].

The effect of reactive magnetron sputtering on the structural and reflective characteristics of multilayer NiMo/C X-ray mirrors is studied in this paper. We noted earlier in Ref. [15] the positive effect of vacuum annealing on the reflectivity of the NiMo/C system. Therefore, here we also investigated the effect of thermal annealing in vacuum on the reflective and structural characteristics of NiMo/C.

1. Experimental methodology

Multilayer NiMo/C structures were produced in this study by direct current reactive magnetron sputtering. Before the start of the technological process, the pressure of the residual gases in the vacuum chamber was at the level of $8 \cdot 10^{-7}$ Torr. High-purity (99.998 %) argon was used as the main working gas, the pressure of which was kept constant during the deposition of structures and amounted to $1.5 \cdot 10^{-3}$ Torr.

The structures were synthesized by sequentially moving the substrate between two magnetrons. One has a carbon target, the other has a nickel-molybdenum alloy target. When the substrate was located above a magnetron with a NiMo target, only argon was supplied to the chamber. During the passage of the substrate over the magnetron with a carbon target, nitrogen purity of 99.998 % was supplied. In this case, the percentage of nitrogen in the vacuum chamber was determined according to the following expression:

$$C_{N_2} = \frac{p_{N_2} + p_{res}}{p_{N_2} + p_{Ar} + p_{res}} \cdot 100\,\%,$$

where p_{res} is the partial pressure of residual gases (negligible), p_{Ar} is the partial pressure of argon, p_{N_2} is the partial pressure of nitrogen. A number of structures were thus produced at $C_{N_2} = 15$ and $C_{N_2} = 30$ %.

The NiMo and C targets with a thickness of 6 mm had a circular shape and an erosion zone diameter of approximately 107mm. The mass content of Mo in the NiMo target was 20,%. The sputtering system was powered by stabilized current sources developed in IPM RAS. The current values were 300 mA for NiMo and 800 mA for C throughout the entire process.

The substrates used in this study with a size of 25×25 mm were cut from standard single-crystal silicon flat plates for the microelectronic industry with an orientation (100) with a diameter of 100 mm and a thickness of 0.46 mm. The effective RMS surface roughness of the substrates was at the level of 0.2–0.3 nm.

The substrates were mounted vertically on a holder, which reciprocated over the targets during spraying. It was possible to control the thickness of the layers applied to the substrate by changing the speed of movement of the holder over the targets (in fact, the time spent by the substrate in the magnetron discharge zone). Layer-by-layer deposition of NiMo and C was performed using this method.

The complete structure has the following form due to the peculiarities of the linear movement of the substrate holder over the targets: Si-substrate/NiMo/[CC/NiMoNiMo]$_N$ CC/NiMo, where N is number of periods, CC and NiMoNiMo are designation of layers of a multilayer mirror sprayed in two passes (there and back) of the substrate holder above the targets, Si-substrate is the silicon substrate. This sequence of materials does not significantly affect the maximum reflectance of mirrors in the first order, i.e. it will be identical to the Si-substrate/[CC/NiMoNiMo]$_N$ structure in terms of the value of the reflection magnitude in the first order. However, there may be a certain difference in the area between the critical angle and the first order of reflection, therefore, in further discussion, by NiMo/C we will mean the complete structure.

The uniformity of the coatings applied to the substrates over the entire area was determined by the shape of precision shaped diaphragms placed between the sprayed target and the substrate. This regulates the spatial distribution of the flow of atoms deposited on the substrate. The specific type of precision diaphragms for each target was determined experimentally. The unevenness of the thicknesses of individual films, the period of the structure, or the total thickness of the mirror over the area of the substrate with a diameter of 100 mm was less than 0.5 %.

The distribution of the period according to the parabolic law is required for working with Gebel mirrors. Shaped diaphragms are also used in this case, but their shape is chosen in such a way as to ensure not a uniform distribution of thicknesses, but a distribution satisfying a given law. The accuracy of reproducing the parabolic law of the period distribution should also be better than 0.5 %.

The NiMo/C samples were annealed in a vacuum (residual gas pressure level $\sim 10^{-7}$ Torr) furnace. The temperature was controlled by a chromel-alumel thermocouple with an accuracy of $\pm 5\,^\circ$C. Each sample was annealed sequentially at two temperatures for 1 h. First at a maximum temperature of $T = 250\,^\circ$C, then at $T = 320\,^\circ$C. The reflective characteristics of the samples were measured before and after each iteration of annealing. The changes that could be caused by annealing were revealed using this method.

A typical time dependence of the sample heating temperature in a vacuum furnace in our experiments is shown in Fig. 1. It took a little more than an hour to reach the operating temperature, then the temperature was kept constant for 1 h, after which it cooled down to room temperature for several hours. As a rule, the cooling sample remained in a vacuum furnace with the heating turned off overnight and was removed to the atmosphere in the morning of the next day. Thus, the duration of thermal exposure to each sample was not limited to 1 h. But the time of exposure of each sample to maximum temperature was exactly 1 h.

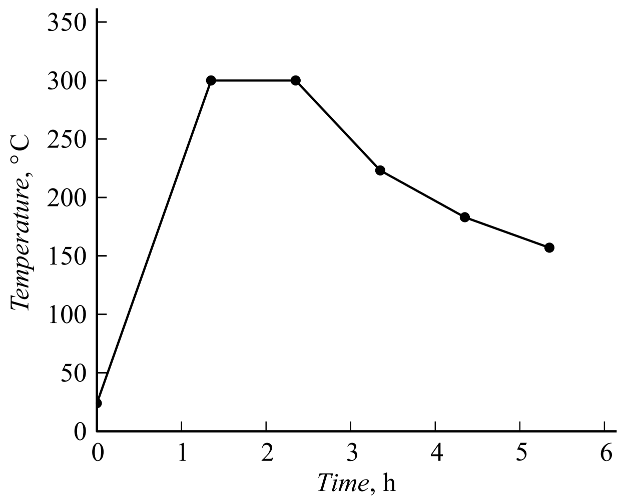

Figure 1. Time dependence of the sample temperature of the multilayer structure NiMo/C when heated to 300 °C.

The reflective characteristics of multilayer structures were measured using a PANalitycal X'Pert PRO MRD four-crystal laboratory diffractometer using small-angle X-ray reflectometry. The sample was placed on a table with six degrees of freedom. X-ray tube was used as the X-ray source with a wavelength of $\lambda = 0.154$ nm (line Cu Kα1). The operating parameters of the X-ray tube were as follows: voltage $U = 30$ kV, electron beam current $I = 20$ mA. Spectral and angular monochromatization of the probe beam was performed using a four-crystal asymmetric monochromator Ge (220). Exit slits further behind the monochromator limited the beam in the horizontal and vertical planes. A holder with a Soller collimator and an inlet slot are installed in front of the gas detector.

To obtain a specular reflection curve, the diffractometer was adjusted so that the sample bisected the Gaussian-shaped X-ray beam. This angular position was taken as zero. The radiation source remained stationary, and the detector, turning at an angular velocity twice as fast as the sample, recorded the intensity of the radiation reflected by the sample. The values of the reflectances given in this paper were determined as the ratio of the radiation intensity (number of photons per second) reflected from the mirror to the intensity of the reference signal. We can talk about the error of the determined values of the reflectances in ± 1 % due to the sufficient exposure time and small statistical fluctuations of photons from the source and electrons in the detector.

The parameters of the X-ray mirrors (periods, thicknesses of the layers of materials and mixed regions) were determined by fitting the mirror reflection curves using the program for the reflectometric reconstruction of multilayer structures „Multifitting“, created in IPM RAS [30] and developed subsequently [31]. It makes it possible to calculate the spectral and angular dependences of the reflectance on the simulated structure by solving a system

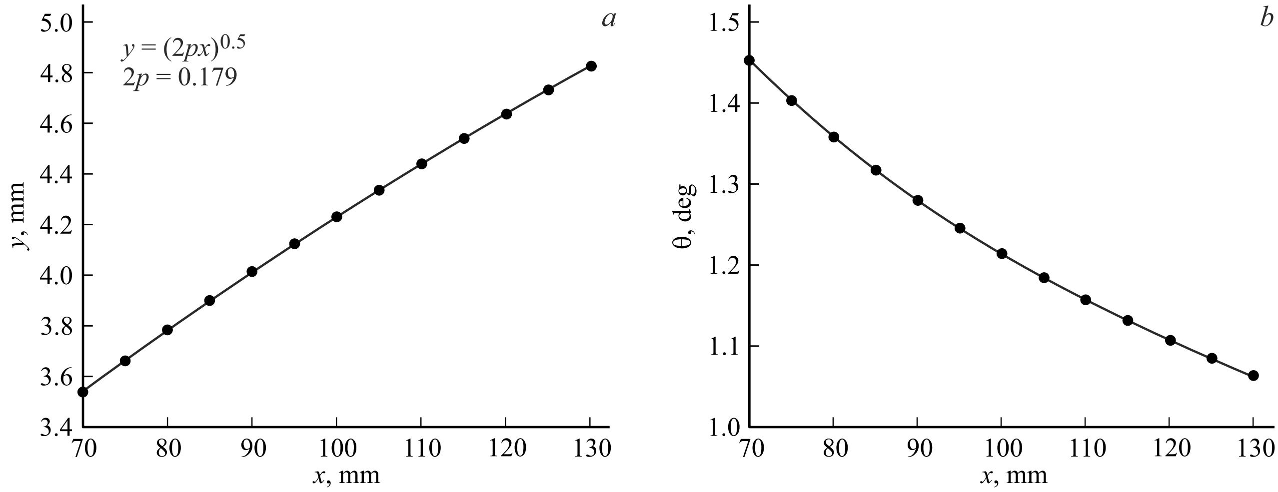

Figure 2. The given equation of the guide of the parabolic mirror (a) and the local grazing angles of radiation (b).

of recurrent relations, as well as to simultaneously fit several experimental curves taken in different spectral ranges.

When choosing the period of the studied multilayer NiMo/C structures, it was necessary to proceed from the really existing systems of collimation of hard X-ray radiation (lines Cu Kα1) emitted from the X-ray tube of the DRON type diffractometer. Calculations were performed using the typical equation of the cylindrical guide surface $y = (2px)^{0.5}$, where $2p = 0.179$, $80 \le x \le 120$ (Fig. 2, a). The corresponding distribution of local radiation grazing angles is shown in Fig. 2, b. The local grazing angle of radiation was defined as the angle between the tangent to the parabola at a given point and the ray leaving the focus (X-ray tube) and passing through this point. With high ($< 0.0013^\circ$) accuracy at $80 \le x \le 120$, the sliding angles can be calculated by taking the derivative $y' = \tan\theta \approx \theta = \sqrt{p/2x}$, where $[\theta] = \text{rad}$.

The extreme (maximum and minimum) values of the radiation grazing angles in the range of values $80 \le x \le 120$ correspond to the periods of the multilayer X-ray mirror of NiMo/C $d \approx 41.5$ and ≈ 33.5 Å. The reflectances are maximal, according to Ref. [14,15], when the proportion of NiMo thickness in the period is $\beta = 0.3{-}0.5$. These parameters were used as the basis for the magnetron sputtering process.

2. Results and their discussion

At the first stage, we worked with mirrors having a period $d \approx 33.5$ Å — the minimum value for a particular Gebel mirror. The carbon target was sputtered at $C_{N_2} = 15\,\%$.

The parameters of a multilayer NiMo/C structure with a period of $d \approx 33.5$ Å, synthesized with a nitrogen content of $C_{N_2} = 15\,\%$ and annealed at maximum temperatures of $T = 250\,^\circ$C and $320\,^\circ$C were determined in the „Multifitting" program (Table. 1) using the results of fitting of mirror reflection curves (Fig. 3, 4).

Table 1. NiMo/C parameters with $d \approx 33.5$ Å at $C_{N_2} = 15\,\%$

T, °C	As-deposited	250	320
N	120		
d, Å	33.68	34.06	34.32
dz, %	0.013	0.013	0.014
β, a.u.	0.460	0.455	0.455
σ (NiMo), Å	4.70	4.50	4.30
σ (C), Å	6.80	6.20	6.10
R, %	71.5	75.4	76.1

Note. R is the reflectance in the first Bragg reflection order at wavelength 0.154 nm, N is the number of periods, β is the proportion of NiMo thickness in the period, σ(NiMo) and σ(C) are RMS values of the widths of interfaces (areas of mixing of materials and roughness) on the surface of the NiMo layers and C accordingly, dz is the linear layer drift.

The actual structure of a multilayer mirror is not strictly periodic. The pressure of gases varies during magnetron sputtering, erosion of the target occurs, therefore, the growth rate of films also changes. This leads to a monotonous increase or decrease in the thickness of the period throughout the depth of the structure. dz in the table means a linear change in the thickness of the layer C and NiMo with an increase in the period number by one, as a percentage of the nominal layer thickness. The average layer thickness for all periods is maintained and is equal to the nominal thickness, i.e. on the one hand, the layers will be thinner, and on the other hand — thicker. This drift can be either positive or negative, i.e., the layers can become thicker deeper into the structure, and they can become thinner. In our case, based on the shape of the experimental peaks, it is difficult to say which layers (Cor NiMo) underwent significant drift and what is the sign (positive or negative)

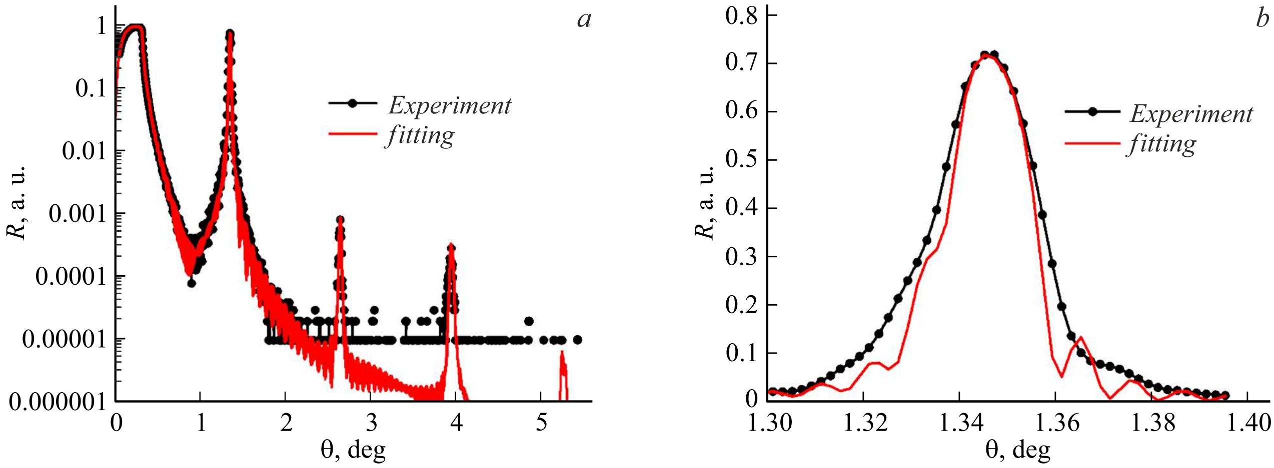

Figure 3. Example of experimental and modeled in „Multifitting“ mirror reflection curves of a NiMo/C sample with $d \approx 33.5$ Å: *a* — general curve, *b* — first order of reflection.

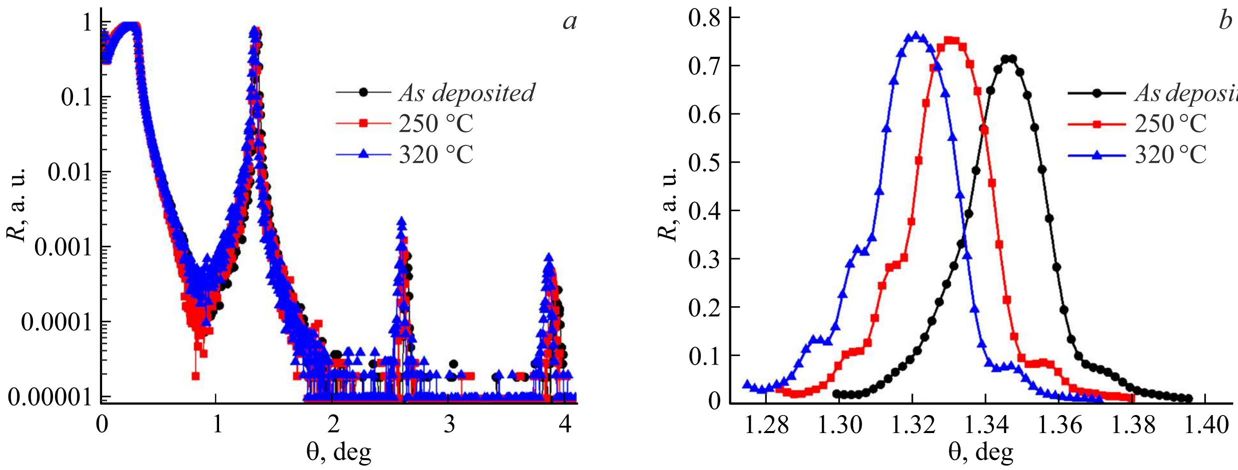

Figure 4. Mirror reflection curves of a NiMo/C sample with $d \approx 33.5$ Åsynthesized at $C_{N_2} = 15\%$ and annealed at 250 and 320 °C: *a* — general curve, *b* — first order of reflection.

of this drift. Therefore, we indicate the absolute value of the drift of both layers (C and NiMo) in the following tables.

The following conclusions can be drawn from the data provided. The structure with carbon atomized in a nitrogen medium has a reflectance of 71.5 % in the first Bragg order. It is shown in Ref. [15] that a structure with the same period, sputtered in an exclusively argon atmosphere, had a reflection of 69 %.

The NiMo/C period increased by 1.9 % after annealing compared to the initial value. The widths of the interfaces on both borders have slightly decreased. There was also a slight (1.1,%) decrease in the share of NiMo in the period. The reflection has grown in all orders. The reflectance increased by 4.6 absolute percent in the first order, from 71.5 % to 76.1 %. For comparison, it was shown in Ref. [15] that the reflectance of a structure made without nitrogen reached 72% after annealing at 320 °C. It was also suggested that the increase in the reflectance after annealing could occur due to the „decompaction“ of the carbon layers and the diffusion of carbon atoms from the transition regions.

Changes in the region between the critical angle and the first order of reflection indicated some transformations in the thickness or roughness of the surface layers of the multilayer NiMo/C structure after annealing.

The structure of NiMo/C with the period $d \approx 41.5$ Å (another extreme value on a parabolic Gebel mirror) was studied at the second stage. The nitrogen content during sputtering was also $C_{N_2} = 15\%$. The structural parameters reconstructed according to the reflectometry data (Fig. 5) are presented in Table 2.

This structure has a reflectance of 78.3,% in the first Bragg order immediately after synthesis (before annealing). For comparison, a structure with a similar period synthesized without nitrogen had 71 % before annealing and 75 % after annealing at a maximum temperature of 320° in Ref. [15].

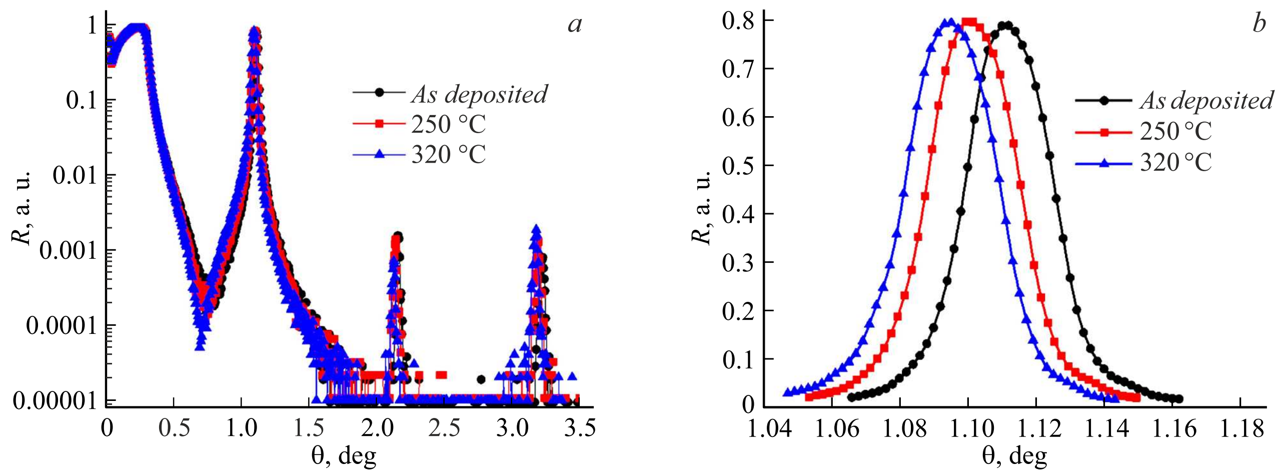

Figure 5. Mirror reflection curves of a NiMo/C sample with $d \approx 41.5$ Åsynthesized at $C_{N_2} = 15\%$ and annealed at 250 and 320 °C: *a* — general curve, *b* — first order of reflection.

Table 2. NiMo/C parameters with $d \approx 41.5$ Å at $C_{N_2} = 15\%$

T, °C	As-deposited	250	320
N	80		
d, Å	41.34	41.75	41.99
dz, %	0.021	0.020	0.021
β, a.u.	0.416	0.408	0.408
σ (NiMo), Å	5.80	6.00	6.20
σ (C), Å	6.80	6.70	6.60
R, %	78.3	79.0	78.8

Table 3. NiMo/C parameters with $d \approx 33.5$ Å at $C_{N_2} = 30\%$

T, °C	As-deposited	250	320
N	120		
d, Å	34.33	34.72	34.88
dz, %	0.01	0.01	0.01
β, a.u.	0.440	0.434	0.434
σ (NiMo), Å	5.90	5.40	5.50
σ (C), Å	5.30	5.60	5.20
R, %	74.6	76.1	77.4

After annealing, the period of the studied mirror increased by 1.6% compared to the initial value. The thicknesses of the interfaces on the C layer decreased, and increased on the NiMo layer. There was also a slight (1.9,%) decrease in the share of NiMo in the period. The reflection decreased in the second order, and increased in the third order, which may indicate a change in the ratio of material thicknesses in the period.

The reflection in the first order of diffraction did not change significantly after annealing. It can be said that it is within the measurement error, formally reaching 79%. Changes in the region between the critical angle and the first Bragg order indicated some transformations of thicknesses or interfaces in the surface layers of the multilayer NiMo/C structure after annealing.

At the next stage, the NiMo/C structure was synthesized with a period of $d \approx 33.5$ Å and a nitrogen content of $C_{N_2} = 30\%$ during sputtering. The structural parameters reconstructed according to the reflectometry data (Fig. 6) are provided in Table 3.

The reflection value in the first order increased (in comparison with the case $C_{N_2} = 15\%$) to 74.6%. The period of the multilayer mirror after annealing increased by 1.6% compared to the initial value. The thicknesses of the interfaces tended to decrease. The reflection in the first order increased to 77.4% after annealing. An increase in the reflectance in the remaining two orders of magnitude can also be attributed to an improvement in the smoothness of the interface between the layers.

The NiMo/C structure was synthesized at the final stage of the study with a period of $d \approx 41.5$ Å with a nitrogen content of $C_{N_2} = 30\%$ during sputtering. The structural parameters reconstructed according to the reflectometry data (Fig. 7) are listed in Table 4.

The reflectance of this mirror has exceeded 80%. A after annealing at a maximum temperature of 320° was 81.4%, which significantly exceeds the result for all previously radiated structures. The thicknesses of the interfaces also tend to decrease after annealing. The period increased by 1.2% after annealing compared to the initial value.

In addition, according to mirror models constructed in „Multifitting“, the drift of layers dz in NiMo/C synthesized at $C_{N_2} = 30\%$ is lower than at $C_{N_2} = 15\%$, which

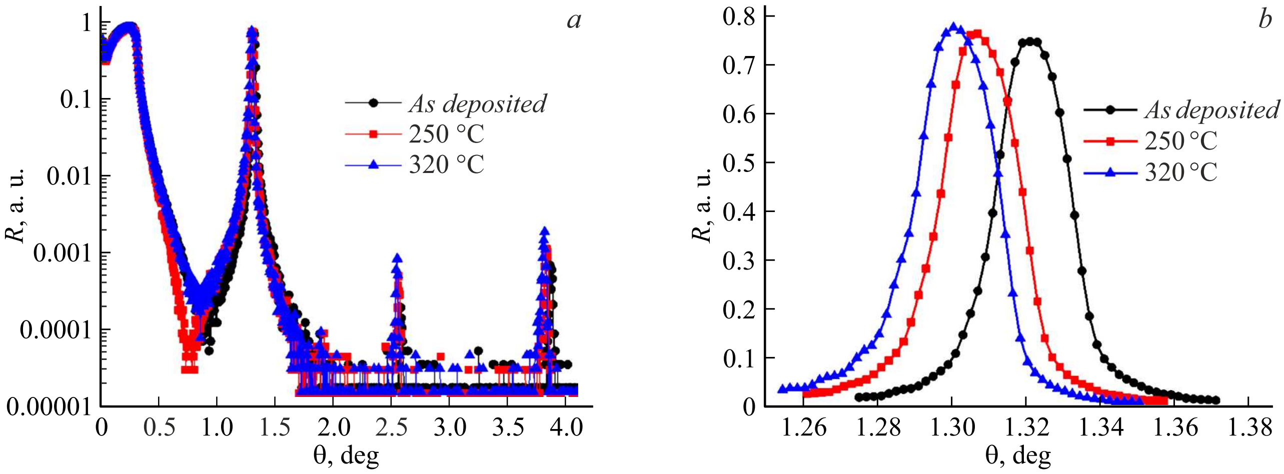

Figure 6. Mirror reflection curves of a NiMo/C sample with $d \approx 33.5$ Åsynthesized at $C_{N_2} = 30\,\%$ and annealed at 250 and 320 °C: *a* — general curve, *b* — first order of reflection.

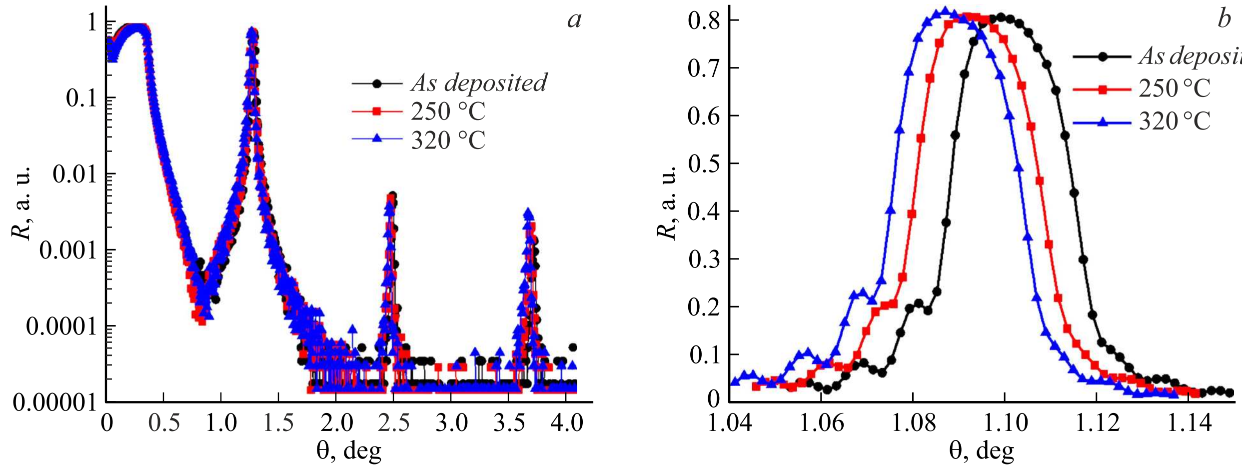

Figure 7. Mirror reflection curves of a NiMo/C sample with $d \approx 41.5$ Åsynthesized at $C_{N_2} = 30\,\%$ and annealed at 250 and 320 °C: *a* — general curve, *b* — first order of reflection.

Table 4. NiMo/C parameters with $d \approx 41.5$ Å at $C_{N_2} = 30\,\%$

T, °C	As-deposited	250	320
N	80		
d, Å	41.78	42.08	42.30
dz, %	0.017	0.017	0.017
β, a.u.	0.412	0.414	0.426
σ (NiMo), Å	5.40	5.50	5.40
σ (C), Å	6.80	6.70	6.40
R, %	80.3	80.4	81.4

could also affect the reflectivity. At the same time, annealing had no significant effect on the value of dz.

Conclusion

Multilayer structures of NiMo/C with periods $d \approx 41.5{-}33.5$ Åsynthesized by reactive magnetron sputtering showed high reflectivity. The magnitude of their reflection exceeds the magnitude of reflection of structures synthesized without nitrogen. Annealing at maximum temperatures of up to 320 °C led to an even greater increase in reflectivity. After annealing of the samples synthesized with a nitrogen content of 15 %, the reflectances in the first order were $R = 78.8\,\%{-}76.1\,\%$ for periods $d \approx 41.5{-}33.5$ Å respectively. $R = 81.4\,\%{-}77.4\,\%$ for structures synthesized with 30 % nitrogen content. This result significantly exceeds the reflection of all previously studied multilayer mirrors, which are used as reflective coatings for Gebel mirrors operating at a wavelength of 0.154 nm.

The values of the transition regions on the C and NiMo layers were in the range of 4–7 Å and, in general, tend to decrease or fluctuate slightly after annealing.

An increase in the peak reflectance in the first order after annealing could be associated with a decrease in the thickness of the transition regions. In addition, a decrease in layer drift was observed in the NiMo/C period after an increase in nitrogen concentration C_{N_2} from 15 % to 30 %.

The demonstrated high reflectivity of NiMo/C multilayer structures suggests that it is a good alternative to the W/Si Gebel mirrors widely used in technology.

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Conflict of interest

The authors declare that they have no conflict of interest.

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