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Beryllium-Based Multilayer Mirrors and Filters for the Extreme Ultraviolet Range

Chkhalo Nikolay[1], Lopatin Alexey[1], Nechay Andrey[1], Pariev Dmitriy[1], Pestov Alexey[1], Polkovnikov Vladimir[1,*], Salashchenko Nikolay[1], Schäfers Franz[2], Sertsu Mewael[2], Sokolov Andrey[2], Svechnikov Mikhail[1], Tsybin Nikolay[1], and Zuev Sergey[1]

[1] Institute for Physics of Microstructures of the Russian Academy of Sciences, GSP-105, 603950 Nizhny Novgorod, Russia
[2] Institute for Nanometre Optics and Technology, HZB-BESSY-II, Berlin, 12489, Germany

This paper presents the first results of systematic studies of beryllium as a material for multilayer mirrors (MLM) and transmission filters (TF) for the EUV spectral range. The objective for the study is the need for the increase in reflectivity and spectral resolution of MLMs for studying the Sun's corona. We investigated Mo/Be (working wavelength is 13.2 nm), Be/Al and Be/Si/Al (17.1 and 30.4 nm) multilayers, as well as free-standing Be films. It was shown that the Be-containing MLMs have significant advantage in reflectivity while their spectral pass-band is similar to beryllium-free MLMs. Observation of the MLMs in the course of 20 months has not revealed any significant decrease in the reflection coefficient. Effect of the silicon interlayers on reflectance of Be/Al MLM is explained. Investigation of a free-standing beryllium filter of the 160 nm thickness showed that its mechanical strength is approximately at the same level as that of the aluminum filter with the same thickness. There is also high stability of the transmittance.

Keywords: Multilayers, Multilayer Design, X-ray Mirrors, Space Optics.

1. INTRODUCTION

The range of extreme ultraviolet radiation with wavelengths of 12–60 nm (EUV) is of considerable interest for solar astronomy, since this range contains a number of important emission lines for multiply charged ions. For example, FeXXIII, FeXXI, FeXX (wavelengths 12.5–14 nm), FeXII–FeIX (17.1–19.5 nm), HeII (30.4 nm), etc. These ions are formed in different layers of the solar atmosphere (from the transitional layer (HeII) to the outer layers of the corona (FeXII)) and correspond to different excitation temperatures (from 0.05 MK (HeII) to 20 MK (FeXXIII)). The imaging of the Sun on the selected lines actually corresponds to the construction of the plasma temperature distribution in individual corona layers.

As a tool for investigating the corona of the Sun there are widely used telescopes based on the two-mirror Ritchey–Chrétien scheme with multilayer mirrors (MLM),[1,2] which simultaneously perform the functions of imaging and monochromatization. The spectral range of the sensitivity of the telescope is finite and is determined by the MLM spectral bandwidth. Therefore, a number of spectral lines formed in different conditions complicate the diagnostics of the coronal plasma (determination of temperature, density) by telescopic images. For example, in the wavelength range 17.7–20.7 nm there get the FeX–FeXXIV ion lines, which are excited in a wide temperature range (from 1 to 16 MK), as well as a number of ion lines of other elements (O, Ca and Ni) corresponding to the temperatures of 0.3–5 MK.[3] This introduces significant uncertainties in determining the temperature composition of the observed plasma. Therefore, it is extremely important to increase the spectral selectivity of multilayer mirrors $\lambda/\Delta\lambda$.

For any particular pair of materials, a decrease in $\Delta\lambda$ can be achieved due to a decrease of the fraction of the scattering (strongly absorbing) material in the MLM period. However, as a rule, this leads to a decrease in the peak value of the reflection coefficient. Therefore, when developing and synthesizing a MLM for future space experiments, it becomes necessary to find the optimal ratio of the spectral selectivity and the reflection coefficient. Ideally, it is required to maintain or even exceed the high

*Author to whom correspondence should be addressed.

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coefficients of existing MLM for solar astronomy,[4–10] and to increase their spectral selectivity.

In fact, this goal can be achieved only by switching over to other materials. However, when selecting new materials, it is necessary to take into account not only their X-ray optical characteristics, but also the long-term (more than 5 years) stability of their reflective characteristics.

Another problem for the developers of future missions to study the solar corona consists in the necessity to increase the radiation resistance and mechanical durability of the input transmission filters (TF) of their telescope. The requirements as to radiation resistance and ability to operate at high temperatures are relevant for the telescopes that will operate in orbits near Mercury.[11,12] The importance of the mechanical strength of the input filters is related to the need to reduce the distortions of the telescope images caused by diffraction on the filter grid.[13,14] This problem is partially solved by increasing the size of the filter cells on the grid. It is obvious that enhancing the mechanical strength by increasing the thickness of the TF leads to a decrease in its transparency at the working wavelengths. Therefore, here again we face the need to find new materials capable of providing maximum transmission at the telescope working wavelengths while increasing the TF mechanical strength.

One of the most interesting and poorly studied materials in the EUV region is beryllium. There are only few works that indicate high reflection coefficients in the 11 nm region, obtained with Mo/Be,[15–17] and in the region of 25 nm obtained with the Ti/Be[18] MLM. Beryllium is of interest because of its relatively low absorption coefficient in a wide band of the EUV range, from the K-edge of 11.2 nm to 40 nm. Accordingly, the use of the TF based on beryllium makes it possible to cover the most interesting range for solar astronomy, namely 13–35 nm, where many intense lines are located. Due to its relatively high melting point, beryllium can also be considered as a component of an input filter for the observatories that will operate in near-solar orbits. The use of a filter of the same composition for different channels of the telescope is important in the case of multi-sector mirrors, since its design is much simpler.

As part of the work on the nanolithography[19,20] and the telescopes of the next generation for the study of the Sun,[10,21] IPM RAS created a certified laboratory for manufacturing MLMs with beryllium. In this paper, we present the results of the first experiments on the reflection coefficients of MLMs and the transmission of the TF on the basis of beryllium in the EUV range.

2. EXPERIMENTAL DETAILS

Multilayer mirrors are deposited on super-smooth (rms roughness value is 0.1–0.2 nm) silicon substrates by magnetron sputtering. The synthesis process is carried out on a magnetron sputtering installation with four magnetrons. This determines the maximum number of materials that can be deposited in a single process. Sputtering was carried out in argon environment with a 99.998% purity at a pressure of 0.08–0.13 Pa. The current varied within 100–1500 mA, the voltage was within 200–400 V, the distance between the target and the substrate varied in the range 70–80 mm. During the deposition process, the substrate rotates simultaneously around its own axis and around the axis of the vacuum chamber. An additional factor that ensures the uniformity (or the required distribution over the surface of the mirrors) of the film thicknesses is the curved diaphragm installed between the magnetron and the substrate. In this paper, the uniformity of the MLM period on a 100 mm substrate was about 1%. The thickness of the deposited layers is controlled by the choice of the speed for the passage over a particular magnetron or the electric power supplied to it. For periodic mirrors, these values are fixed for the entire time of the technological process, which ensures a high level of periodicity of the growing structure.

Thin freestanding films were produced according to the previously developed technique with the use of a sacrificial layer deposited between the substrate and the film, which dissolves in the process of selective etching.[21,22] This technique implies the contact of the film with the etchant during the dissolution of the sacrificial layer. For the production of defect-free films from active materials such as beryllium, it is necessary to find a special sacrificial layer and a selective etchant. It was found that freestanding Be films can be released from the substrate by liquid etching of a sacrificial Mg layer in acetic acid.

The parameters of the structures (period, individual layer thicknesses, element density, interlayer roughness) were determined by fitting the reflection curves at a wavelength of 0.154 nm. The parameters of fitting were individual film thicknesses, film material densities and interlayer roughnesses that are generally different at different boundaries of the MLM period. The fitting procedure is described in Ref. [23]. The experiments were done on a Philips X'Pert Pro four-crystal diffractometer.

Measurements in the EUV spectral region were carried out both in the laboratory and on the BESSY-II synchrotron. Two laboratory reflectometers equipped with grating spectrometers-monochromators RSM-500 (spectral range of 4–25 nm, resolution 0.03 nm) and LHT-30 (range 25–200 nm, resolution 0.1 nm) were used.[24,25] The radiation source for the monochromator RSM-500 is a demountable X-ray tube with replaceable anodes.[26] The LHT-30 monochromator is equipped with a gas discharge radiation source.[24] Synchrotron measurements in the EUV range were performed on a UHV triaxial reflectometer on the optical line of the storage ring BESSY-II.[27] We studied angular (at a fixed photon energy) and spectral (at a fixed angle of radiation incidence) reflectivity dependencies of MLM, and the spectral transmissivity dependencies of the TF at normal incidence. Figure 1 compares the

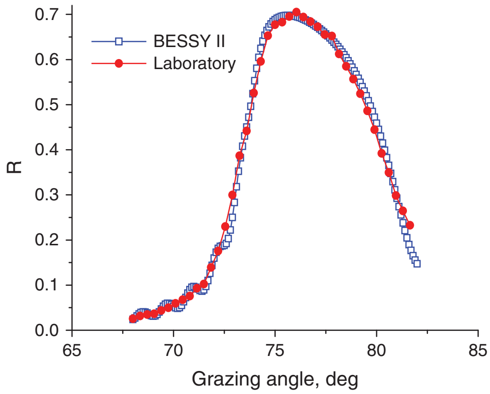

Figure 1. Angular dependencies of the reflection coefficient of the Mo/Be mirror, measured on a laboratory reflectometer[22] and on BESSY-II.[24] The wavelength is 11.34 nm.

reflectance characteristics obtained on a laboratory reflectometer and on BESSY-II. One can see good (at a level of $\pm 1\%$) agreement and consistency of the experimental data. Therefore, hereinafter we mainly present the results of studies on the laboratory reflectometers and estimate the accuracy of these measurements $\pm 1\%$. Periodically we conduct appropriate cross-tests, confirming the accuracy of measurements in different spectral ranges. For this purpose, the laboratory has sets of mirrors measured on BESSY-II, which serve as secondary standards.

3. RESULTS AND DISCUSSION

3.1. Multilayer Mirrors Mo/Be for $\lambda = 13.2$ nm

To register the FeXX, FeXXI and FeXXIII lines at 13.2 nm (one of the channels of the telescope TREK under development[28]), the MLMs with a spectral bandwidth $\Delta\lambda \leq 0.35$ nm are required (for detuning from the adjacent ion lines–FeXIX, FeXXII ~12 nm). Traditionally, the Mo/Si MLMs with a reflection coefficient of $R \approx 70\%$ are used in this range. However, the Mo/Si MLM optimized for the maximum reflection has $\Delta\lambda$ of about 0.5 nm, which is one and a half times higher than the required value for the telescope. It is possible to reduce the value of $\Delta\lambda$ by decreasing the proportion of molybdenum in the structure, but the peak reflection coefficient will inevitably fall.

Figure 2 shows the refractive index decrement (δ) and the absorption index (γ) in $n = 1 - \delta + i\gamma$ of molybdenum, silicon and beryllium in the 11–14 nm region. The calculations were performed using the data.[29] It can be seen that beryllium has a smaller absorption. Moreover, the difference between the additions to the real part of the refractive indices δ_{Mo}–δ_{Be} is less than the difference δ_{Mo}–δ_{Si}. Both these factors may lead to a higher radiation penetration depth for the Mo/Be structure than for the Mo/Si one. And this means that we can expect greater selectivity of the Mo/Be mirrors compared with the Mo/Si ones.

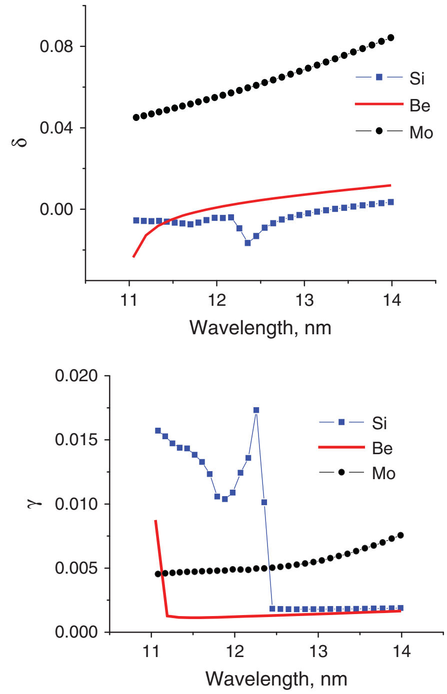

Figure 2. Dispersive additions to the refractive indices ($n = 1 - \delta + i\gamma$) of molybdenum, silicon and beryllium in the 11–14 nm region.

To compare the selectivity and reflection coefficients, a set of Mo/Be and Mo/Si with a different fraction of molybdenum β_{Mo} was fabricated and studied in the MLM period. Figure 3 shows the relationship between the peak values of the reflection coefficients R and the spectral width $\Delta\lambda$ from β_{Mo}. Figure 3(a) corresponds to Mo/Si, Figure 3(b))-Mo/Be MLM.

It can be seen from the data given above that for the same spectral width $\Delta\lambda$ the peak reflection coefficients of the samples under study differ markedly. For $\Delta\lambda =$ 0.35 nm they are: $R = 53\%$ for Mo/Si and $R = 58\%$ for Mo/Be. Taking into account the two reflections in the Ritchey–Chrétien telescope, the gain in the luminosity will be 1.2 ($R^2 = 28.1\%$ for Mo/Si and $R^2 = 33.6\%$ for Mo/Be). For this reason, we consider the Mo/Be pair as an alternative to Mo/Si in the spectral region of about 13 nm, and not only in the 11.1–12.4 nm region.

3.2. Multilayer Mirrors Be/Al for $\lambda = 17.1$ nm

One of the most informative spectral ranges of solar radiation is in the vicinity of the 17.1 nm wavelength. The radiation lines of the FeIX ions are located here. Their registration is used, among other things, to detect the active regions of the corona responsible for the formation of micro-flares, which are one of the smallest processes of energy release in the solar atmosphere. Their nature and origin remain the subject of scientific research and discussion. The ARCA observatory is currently being developed

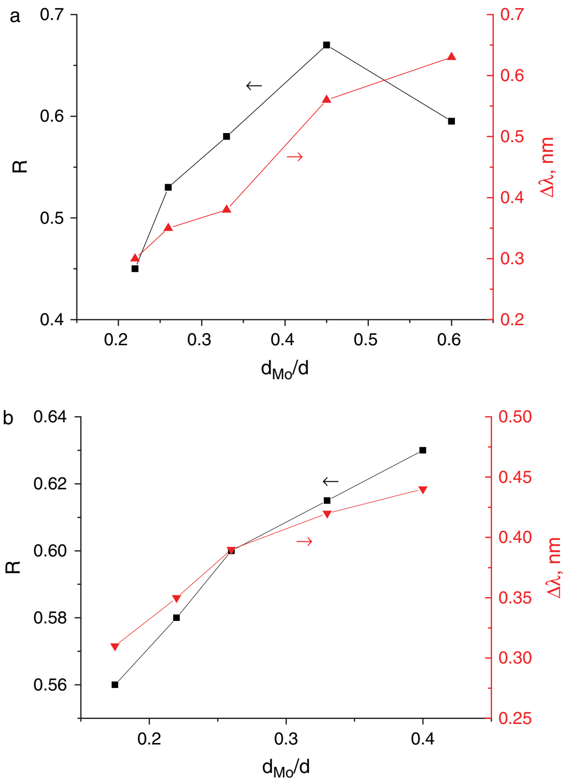

Figure 3. Dependencies of the peak values of the reflection coefficients R and their spectral widths $\Delta\lambda$ on β_{Mo}. (a) Corresponds to Mo/Si, (b) to Mo/Be MLM.

to solve this problem by providing a record high spatial, spectral and temporal resolution.[14] The lines of the FeX (17.5 nm) and FeXII (19.5 nm) ions are of similar interest.

To resolve adjacent lines (for example, FeIX and FeX), the spectral bandwidth of the multilayer mirrors for the 17.1 nm channel of the ARCA Observatory (and for the 17.5 nm channel of other Observatory) should not exceed 0.42 nm. Unfortunately, almost all MLMs, previously developed for the spectral range near 17.1 nm, exceed this value after optimization of the composition for a maximum of the reflection coefficient. Table I shows the reflection and transmission coefficients of the currently applied multilayer structures for a given wavelength. As can be seen from the table, all of the MLMs do not provide the required spectral selectivity. So Mo/Si have $R = 54\%$ and $\Delta\lambda = 0.875$ nm; Mo/Al/B_4C have $R = 55.5\%$, $\Delta\lambda = 0.875$ nm, and Mo/Al/SiC-$R = 53.4\%$, $\Delta\lambda = 0.76$ nm. The Zr/Al MLM has better resolution with comparable reflection coefficient: $R = 56\%$, $\Delta\lambda = 0.6$ nm. The lowest value of $\Delta\lambda = 0.48$ nm, which is close to that required for the telescope being developed, can be offered by the Si/Al structure. But, unfortunately, it also has the lowest reflection coefficient $R = 48\%$.

Table I. Measured characteristics of MLM at $\lambda = 17.1$ nm.

MLM	R, %	Δλ, nm
Mo/Si[30]	54	0.875
Al/Mo/SiC[5,6]	53.4	0.76
Al/Mo/B_4C[5,6]	55.5	0.875
Zr/Al[31]	56	0.6
Si/Al[10]	48	0.48

Figure 4 shows the refractive index decrement (a) and the absorption index (b) parts of the refractive index for zirconium, silicon, aluminum (materials for which the best spectral resolution was obtained) and beryllium in the wavelength range $\lambda = 17$–22 nm. It can be seen from the figure that the jump in the real part of the refractive index at the Be–Al boundary is higher than in the case of Si–Al, which indicates that Be can be considered as a "scattering" material and we can expect a higher MLM reflection coefficient. Moreover, since the absorption of Be is small, one can expect a high spectral selectivity.

Figure 5 shows the results of a comparison of the reflective properties of Zr/Al, Si/Al and Be/Al MLM at normal incidence with a maximum reflection coefficient at a wavelength of 17.5 nm. Calculations are made for "ideal" structures (tabular densities, zero roughness), the composition of which is optimized for a maximal reflectivity. As can be seen from the figure, Be/Al has spectral selectivity that is close to that of Si/Al and a peak reflection coefficient close

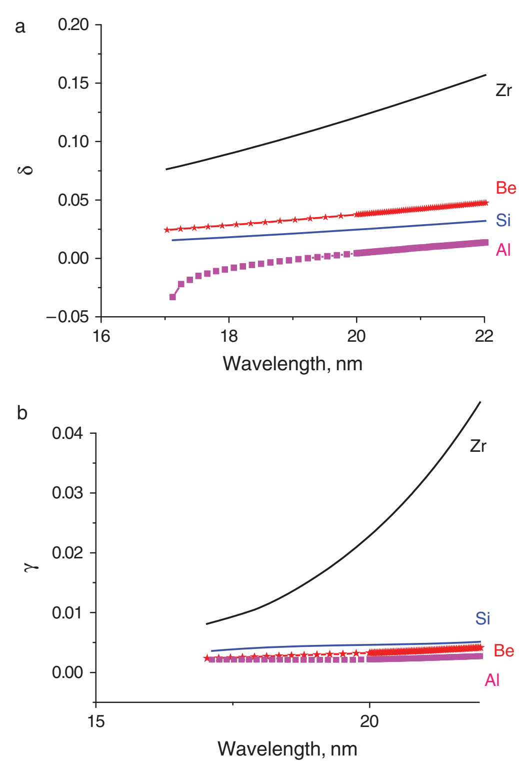

Figure 4. Dispersive additives to the real (a) and imaginary (b) parts of the refractive index for Zr, Si, Al, and Be.

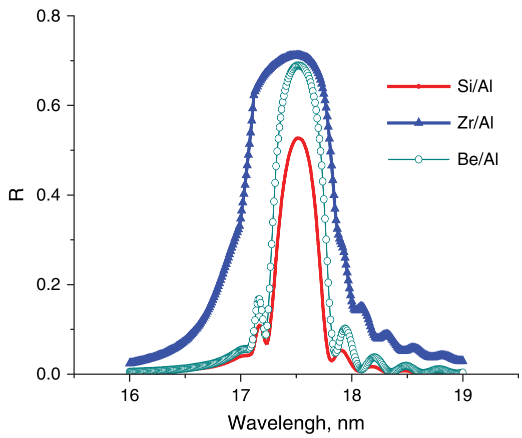

Figure 5. Calculated spectral dependencies of the reflection coefficients of Zr/Al, Si/Al and Be/Al MLM at normal incidence. The calculations are made for "ideal" structures with a tabular density of materials and zero roughness, the composition of which is optimized for a maximum of the reflection coefficient.

to that of Zr/Al. I.e., Be/Al combines both record reflection coefficients and spectral selectivity.

To study the X-ray optical properties of the Be/Al MLM in the vicinity of 17.1 nm wavelength, a series of samples was produced. While the expected R is 69% and $\Delta\lambda$ is 0.45 nm, the real reflectance $R = 46\%$ and $\Delta\lambda = 0.4$ nm (the number of periods is 60, the fraction of beryllium in the period $\beta_{\mathrm{Be}} = 0.55$, the second line of Table II) was obtained on the best samples. Based on the results of the joint fitting of the reflection curves at wavelengths of 0.154 and 17.1 nm, it was found that the reason for the smaller reflection coefficients, in comparison with the theory, is large interlayer roughness $\sigma = 1.3$ nm.

From work[10] it is known that in the Si/Al MLM the interlayer roughness value is $\sigma \approx 0.6$–0.7 nm. Therefore, we studied the effect of introducing thin silicon layers on the boundaries quality and on the reflection coefficients of the Be/Al MLM. We prepared a series of samples with various thicknesses of silicon interlayers deposited on various boundaries: Be–Si–Al, Al–Si–Be and on both boundaries: Be–Si–Al–Si. Table II gives the best results of experiments with the Si interlayers at various boundaries. The optimum thickness of the interlayer was 1 nm.

Table II. Reflection coefficients of Be/Al MLM with the Si interlayers and without them. The experimental reflection coefficients R_{exp} correspond to the highest values obtained. The order of the layers is given from the substrate.

MLM	R_{theor}, %	R_{exp},%
Be/Al	76.3	46
Al/Si/Be	75.3	51
Be/Si/Al	73.5	61
Be/Si/Al/Si	73.7	56

As follows from the table, the MLM with the Be–Si–Al structure of period (Si was deposited on the Be surface) has the highest reflection coefficient, and the optimum silicon thickness is 1 nm. The increase in the reflection coefficient is due to the smoothing of the roughness at all boundaries to $\sigma = 0.6$ nm. We explain this fact by amorphization of metallic films. During the growth of the Al film, the crystallites do not have time to develop to the same dimensions as are characteristic of the Al/Be MLM.

The measured half-width of the reflection peak $\Delta\lambda$ was 0.4 nm, which meets the requirements for mirrors of solar telescopes. It makes this pair of materials the most promising for observatories at a wavelength of 17.1 nm.

3.3. Multilayer Mirrors Be/Al for $\lambda = 30.4$ nm

The HeII radiation line (30.4 nm) is important from the point of diagnostics of the Sun's transition layer. The MLMs based on a pair of Mo/Si materials (peak reflection coefficient $R = 20\%$, spectral selectivity $\lambda/\Delta\lambda \approx 20$) had been used before for this range.[32] As an alternative to the Mo/Si-based mirrors, the multilayer structures based on Mg were considered. However, the disadvantage of Mg is its high chemical activity and, in particular, its susceptibility to oxidation. As demonstrated in Ref. [31], the reflective characteristics of the Si/Mg mirrors are rapidly deteriorating. The application of barrier layers from Cr and B_4C has partially solved the problem. Still, there is a decrease in the peak value of the reflectivity from the initial 38% to 30%. This value is maintained for at least five years. Similar instability characterises the SiC/Mg MLM. With an initial reflection of 42–44% ($\lambda/\Delta\lambda \sim 20$), a decrease of up to 30% in five years was recorded in Ref. [8].

As noted earlier, new missions require structures with better spectral resolution. In particular, the project under development[14] requires spectral selectivity of almost 1.5 times higher ($\lambda/\Delta\lambda \sim 30$). The problem of increasing the selectivity of the Mg-based structures is further complicated by the fact that a decrease in the share of a highly absorbing material in the MLM leads not only to a drop in the reflection coefficient, but also to weakening of the structure resistance to Mg oxidization. One can expect an increase in the rate of degradation of the reflection coefficient for such Mg-containing mirrors.

In this paper, alternative coatings based on Be/Si/Al are being studied for the first time. Figure 6 shows the theoretical spectral dependencies of the reflection coefficients for the most optimal MLM among magnesium-based mirrors and the Be/Al structure. Table III shows the peak values of the reflection coefficients R of these mirrors, as well as the their spectral widths at half-height $\Delta\lambda$.

As follows from the calculations, the Be/Al structure has one of the best values of spectral selectivity (the ratio $\lambda/\Delta\lambda$), though its reflectivity is lower than that of the Mg-based MLM.

Figure 7 shows the angular dependencies of the reflection coefficient of the Be/Si/Al mirror at a wavelength of

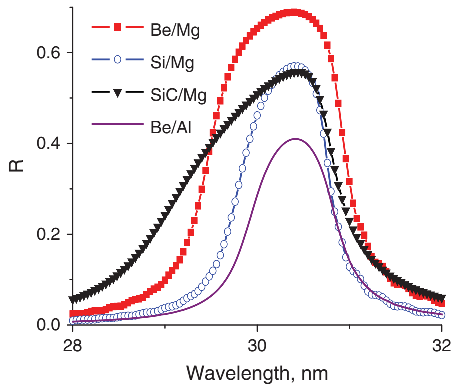

Figure 6. Calculated spectral dependencies of the reflection coefficients of the most optimal MLM among magnesium-based mirrors and the Be/Al structure.

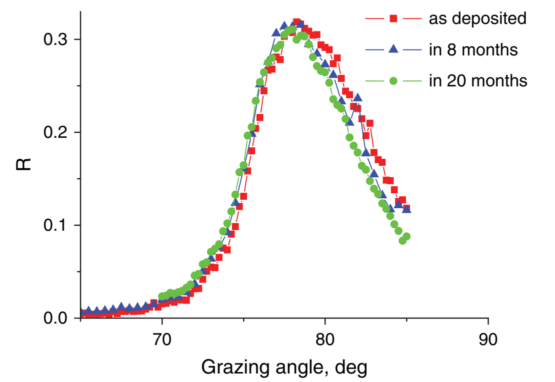

Figure 7. Angular dependencies of the reflection coefficient of the Be/Si/Al mirror at a wavelength of 30.4 nm immediately after the deposition, after 8 months and after 20 months after the deposition.

30.4 nm immediately after the deposition, after 8 months and after 20 months after the deposition. The synthesized structure of Be/Si/Al showed practically unchanged reflective characteristics: $R = 31.5\%$, $\Delta\lambda \sim 0.8$ nm at 30.4 nm wavelength.

Thus, the Be/Si/Al MLMs proposed in this paper, significantly exceed the Mg-based mirrors in spectral selectivity and temporal stability while having similar peak reflectivity.

3.4. Be Transmission Filters for the Spectral Range 11–35 nm

Freestanding multilayer thin films made of Zr/Si and Al/Si were used as blocking filters in the Russian TESIS solar observatory launched in 2009.[33] Since the Al/Si film becomes opaque at $\lambda < 17$ nm, the Zr/Si filter was used at a wavelength of 13.2 nm. The sets of different filters are often used in modern solar EUV telescopes as well. Such an approach complicates the scheme of the spacecraft experiment because some additional gear (the filterwheel assembly) is necessary to replace filters. The use of only one filter with the spectral window covering the whole working range would be much more convenient.

Beryllium is a material with one of the lowest absorption coefficients in the EUV spectral region. This paper is the first to study a possibility of creating thin freestanding Be films for their use as filters in the spectral range 11–35 nm. The spectral dependence of the transmittance of a 160 nm thick Be film is shown in Figure 8. The asterisks represent the experimental data measured on several characteristic lines; the solid line is the calculated dependence, which takes into account two outer layers of BeO, each 3.5 nm thick.

It is noteworthy that the same amount of the surface beryllium oxide was obtained from the reconstruction of the polarizability profile at $\lambda = 0.154$ nm. In this case, the term "polarizability profile" means $\mathrm{Re}(1-\varepsilon)$. Figure 9 shows the measured and fitted reflectivity curves for a Be film sputtered onto a Si substrate, as well as the reconstructed profile of the real part of the polarizability. When the profile was restored (Fig. 9(b)), the imaginary part of the dielectric constant was taken equal to zero. The polarizability profile demonstrates a physically reasonable picture: the presence of transition regions between the external medium and the film material, between the film

Table III. Comparison of the calculated reflective properties of the most promising MLM based on Mg and Be/Al.

MLM	R, %	$\Delta\lambda$, nm
Be/Mg	68.5	1.52
Be/Al	41	1
Si/Mg	57	1.04
SiC/Mg	55.7	1.84

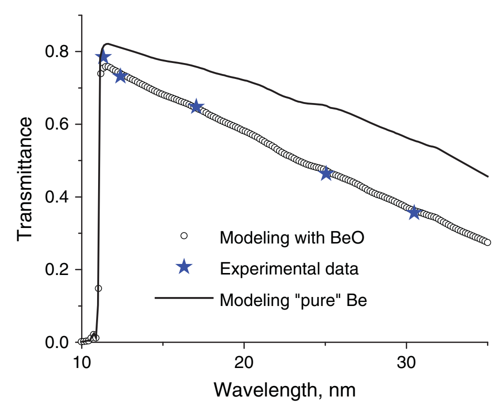

Figure 8. Spectral dependence of the transmittance of a 160 nm thick Be film. The asterisks represent the experimental data measured on the characteristic lines BeKα (11.4 nm), SiLα (13.5 nm), AlLα (17.1 nm), MgKα (25.0 nm) and HeII (30.4 nm). The calculated dependence (scatter line) takes into account the presence of beryllium oxide on the film's surfaces. The fitting gives 3.5 nm of BeO on each side. Other calculated dependence (solid line) show of the transmittance of a 160 nm thick Be film.

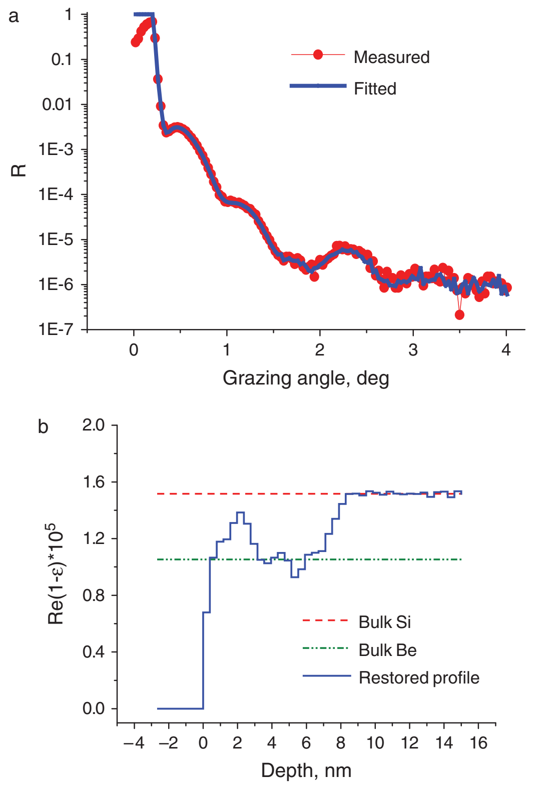

Figure 9. (a) Reflectivity of a Be film sputtered onto a Si substrate at $\lambda = 0.154$ nm. (b) The polarizability profile of the film.

material and the substrate, and the transition to the uniform substrate. A beryllium film, as can be seen from Figure 9, contains a denser layer (apparently, BeO) which is about 3.5 nm in thickness.

Thus, it is shown that Be films can also be used as transmission filters in a wide spectral range of 11.2–35 nm. For the practical application of Be as the basic material of the film transmission filters for solar studies, its mechanical properties and thermal stability have to be investigated. The first experiments showed that beryllium films, in the first approximation, are not inferior in mechanical strength to aluminum films of the same thicknesses.

4. CONCLUSIONS

The article has presented the first results of systematic studies by IPM RAS of beryllium as a material for multilayer mirrors and transmission filters for the EUV range. Beryllium films and multilayer mirrors were deposited by magnetron sputtering in an argon medium. The structural and X-ray optical characteristics were studied with the use of both the synchrotron-based and laboratory reflectometers. The measurement accuracy of the laboratory reflectometers was determined by comparing the reflectivity of the reference mirrors measured on the BESSY-II synchrotron in different spectral ranges. The aim of the work was investigation of the X-ray optical characteristics of MLM and TF, and comparison of their properties with the parameters of traditional MLM used in the EUV range. The study was motivated by new requirements for the characteristics of the X-ray optical elements of the designed telescopes for the study of the Sun's corona. In particular, an increase in the reflectance and spectral resolution of mirrors is required, while maintaining the long-term stability of the X-ray optical characteristics. Additional requirements are imposed on the TF as to the mechanical and radiation resistance.

The main results of the study were as follows.

First, the advantage of the Mo/Be mirrors over the Mo/Si ones in the vicinity of the 13.2 nm wavelength has been experimentally shown. With the same mirror bandwidth of 0.35 nm, the gain in the performance of the two-mirror system was 20%.

Second, at a wavelength of 17.1 nm, the Be/Al MLM with a 1 nm silicon interlayer deposited on the Be films allowed to achieve the record reflection coefficients of 61% with a spectral bandwidth of 0.4 nm. It has been shown that the silicon interlayer reduced the interlayer roughness from 1.3 nm to 0.6–0.7 nm. Apparently, it prevents the crystallization of the Al films.

Third, at a wavelength of 30.4 nm the Be/Al MLM with a silicon interlayer provided a record-breaking bandwidth $\Delta\lambda \sim 0.8$ nm at a reflection coefficient of 31.5%. There is high stability of the reflection coefficient. In contrast to the traditional Mg-containing MLM, the Be/Si/Al structure did not show any significant decrease in the reflection coefficient during the last 20 months. An additional fact that confirms high stability of the MLM based on beryllium is that the depth of the oxidized beryllium layer, measured both from the reflection of the hard X-rays and from the transmission in the EUV range, coincided, and amounted to about 3.5 nm.

Fourth, the freestanding beryllium filter with a thickness of 160 nm has been developed and studied in EUV range for the first time. It has been found that its mechanical strength is approximately the same as that of aluminum. Moreover, the transmission coefficient of the Be TF is also stable like that of the aluminum one. However, unlike the Al filter, the Be filter has a short-wave boundary of 11 nm, which allows to cover the range of 11–35 nm, while the Al filter can be used only at $\lambda > 17$ nm.

Thus, the results of the first experiments have demonstrated significant advantages of the Be-containing MLM and TF over a number of key parameters in the EUV range. The Be-based structures will definitely find application in the planned experiments on the study of the corona of the Sun.

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