B_4C/Mo/Si high reflectivity multilayer mirror at 30.4 nm

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The B_4C/Mo/Si high reflectivity multilayer mirror was designed for He-II radiation (30.4 nm) using the layer-by-layer method. The theoretical peak reflectivity was up to 38.2% at the incident angle of 5°. The B_4C/Mo/Si multilayer was fabricated by direct current magnetron sputtering and measured at the National Synchrotron Radiation Laboratory (NSRL) of China. The experimental reflectivity of the B_4C/Mo/Si multilayer at 30.4 nm was about 32.5%. The promising performances of the B_4C/Mo/Si multilayer mirror could be used for the construction of solar physics instrumentation.

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In solar physics, imaging of solar corona by selecting Fe IX (λ = 17.1 nm), Fe XII (λ = 19.5 nm), Fe XV (λ = 28.4 nm) and He II (λ = 30.4 nm) emission lines[1] required the high reflectivity multilayer mirrors. In recent years, the development of multilayer technology has enabled the construction of new instrumentation and led to a number of successful missions including solar and heliospheric observatory/extreme ultraviolet imaging telescope (SOHO/EIT) and transition region and control explorer (TRACE)[1,2]. The Si-based multilayers can offer significantly higher reflectance and greater spectral selectivity in the range of 13—35 nm[3,4].

In order to improve the reflectivity, Boher *et al.* have studied theoretically and experimentally the periodic structures with three or four materials in the wavelength range of 1.3—6.8 nm[5]. Larruquert has developed a theory on quasi-periodic multi-component multilayers made of highly absorbing materials and established a material selection criteria[6]. A new multilayer optimization method has been developed based on a layer-by-layer calculation[7]. Although the high reflectivity can be obtained up to 53.6% at 30.4 nm by using aperiodic multilayer structure with up to ten materials[8], the fabrication is very difficult for the multi-material multilayers. The physical property (such as roughness and diffuseness) of the material and the calibration of the deposition rate must be considered in practice.

In this paper, the B_4C/Mo/Si high reflectivity multilayer mirror was designed for He-II radiation (30.4 nm) using the layer-by-layer method. Then, the B_4C/Mo/Si multilayer was fabricated by using the magnetron sputtering method and measured by synchrotron radiation (SR) at the National Synchrotron Radiation Laboratory (NSRL) of China.

The layer-by-layer design method can provide a rule of selecting material in order to optimize the reflectivity. The optical constants of various materials at the wavelength of 30.4 nm are plotted in Fig. 1, which were derived from the atomic scattering factors and obtained from the Center of X-ray Optics worldwide web server at Lawrence Berkeley National Laboratory[9] of USA.

From Fig. 1, it can be seen that the refractive index contrast between B_4C and Si is low, and this may induce a relative indetermination on the respective thicknesses of these two layers. According to the layer-by-layer design method, the B_4C, Mo, and Si were chosen[7]. In order to determine the saturated layer number, the reflectivity as a function of the layer number was calculated, as plotted in Fig. 2(a). For each layer, the thickness was optimized

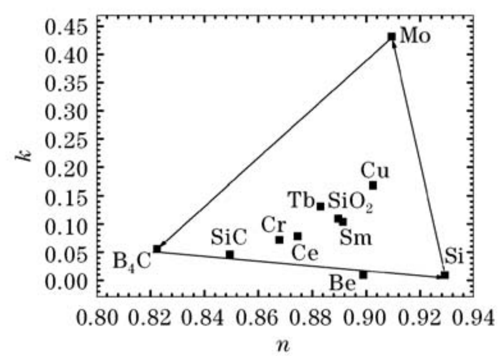

Fig. 1. Representation in the complex plane of the refractive indices of the materials at the wavelength of 30.4 nm. n and k indicate the real and imaginary parts of the refractive indices, respectively.

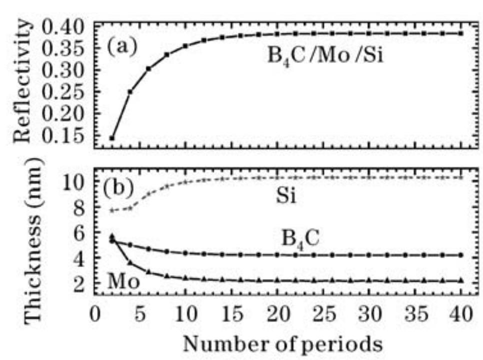

Fig. 2. (a) Optimized reflectivity of B_4C/Mo/Si multilayers, (b) optimized layer thicknesses of Mo, B_4C, and Si versus number of periods of multilayer.

Table 1. Structural Parameters of Design and Those Fitted by XRD and Synchrotron Radiation Reflectivity Data for the B_4C/Mo/Si Multilayer

Layer	Thickness (nm)			Roughness (nm)	
	Design	XRD Fitted	SR Fitted	XRD Fitted	SR Fitted
Substrate	∞	∞	∞	0.3	1.45
Si	10.26	10.65	11.01	0.334	1.19
Mo	2.18	2.71	1.61	0.314	1.10
B_4C	4.20	3.90	4.03	0.339	0.98

in order to obtain the highest reflectance at 30.4 nm, and the optimized results are shown in Fig. 2(b). It can be seen that the reflectivity reaches the maximum when the number of period reaches to 20. Meanwhile, the layer thicknesses approach to constant. After optimization, the theoretical reflectivity is 38.2% at the incident angle of 5°, and the layer thicknesses in the periodical structure are 4.20/2.18/10.26 nm for B_4C, Mo, and Si materials, respectively. As a comparison, the Mo/Si multilayer only shows reflectivity of 22.9% at this wavelength, and it is obviously demonstrated that the addition of a third material B_4C to the Mo/Si multilayer could improve the reflectivity significantly.

After design and optimization, the B_4C/Mo/Si multilayers were fabricated by an ultrahigh vacuum direct current magnetron sputtering deposition system (JGP560C6, SKY Inc., China) in Ar (99.999%) gas[10,11]. The base pressure was less than 8×10^{-5} Pa before deposition, and the working pressure was 0.1 Pa of Ar gas. The sputtering power kept constant. The multilayers were deposited on 20 × 30 (mm) silicon substrates at room temperature. Then, the deposited multilayers were measured, for quality control and depositing rate control, using a small angle X-ray diffractometer (XRD, D1 system, Bede Ltd., UK).

Figure 3 shows the measured XRD data and the fitting curve of B_4C/Mo/Si multilayers. The parameters of the fitting curve are listed in Table 1. All fitting interfacial roughnesses listed in Table 1 are very low (less than 0.4 nm).

The performances of the B_4C/Mo/Si multilayers were measured by reflectivity-meter on beam line U27 at NSRL. The mono-chromator grating (600 line/mm) with the spectral resolution $\lambda/\Delta\lambda$ above 192 was used in the measurement. The aluminum filter was inserted into the

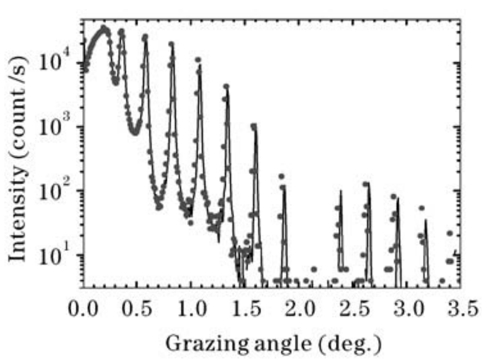

Fig. 3. Small-angle XRD data (dots) and the fitting curve of B_4C/Mo/Si multilayer measured by XRD working at Cu-Kα line (0.154 nm).

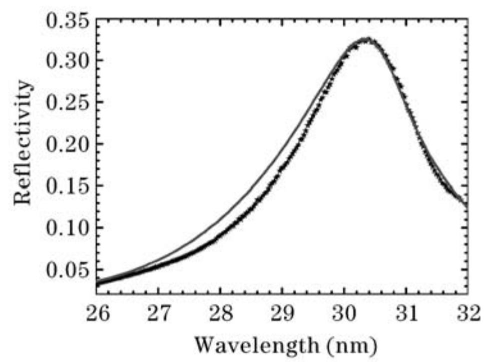

Fig. 4. Reflectivity of B_4C/Mo/Si multilayer at normal incident angle of 5° measured by synchrotron radiation at NSRL. The fitting curve is shown by the solid line, and the fitting parameters are given in Table 1.

beam to improve the spectral purity. The measured reflectivity was shown in Fig. 4. At the normal incident angle of 5°, the measured reflectivity of the sample was up to 32.5% at the wavelength of 30.4 nm. The fitting for the measured reflectivity has been performed using the computer code based on Levenberg-Marquardt algorithm. The fitting layer thickness and roughness, compared with the XRD fitting results, are listed in Table 1. We found a large discrepancy in layer thickness and roughness fitted from XRD and synchrotron radiation measured data. The discrepancy may be explained by the optical effects amorphous B_4C-Mo, Mo-Si and Si-B_4C interlayer, which have optical constants that differ from the pure B_4C, Mo or Si layers[12]. Because the actual density and composition of the interlayer cannot be determined, it is difficult to model the XRD and synchrotron radiation reflectance data accurately and reconcile the apparent discrepancies in the fitting parameters. In this aspect, further investigation will be needed. The roughness and interlayer diffuseness is the main reason why the measured reflectivity is lower than the theoretical one (38.2%), and the contamination of the materials and oxidation of the surface layers before measurement is another possible explanation.

In summary, the B_4C/Mo/Si multilayer for He-II radiation at 30.4 nm was designed using the layer-by-layer method, which could provide high reflectivity when a third material was added to a traditional Mo/Si multilayer. The three-material multilayers were fabricated using the magnetron sputtering machine and measured at NSRL. The measured reflectivity of this multilayer was as high as 32.5%. Moreover, the boron carbide is also a good capping layer, and the peak reflectance and peak position will not shift even after the sample is stored in air for a long time. The high reflective B_4C/Mo/Si multilayer mirrors can be used in astrophysics applications.

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