

SiC/Mg multilayer reflective mirror for He-II radiation at 30.4 nm and its thermal stability

Jingtao ZHU (✉)¹, Da XU¹, Shumin ZHANG¹, Wenjuan WU¹, Zhong ZHANG¹, Fengli WANG¹, Bei WANG¹, Cunxia LI¹, Yao XU¹, Zhanshan WANG¹, Lingyan CHEN¹, Hongjun ZHOU², Tonglin HUO²

¹ Institute of Precision Optical Engineering and Technology, Physics Department, Tongji University, Shanghai 200092, China
² National Synchrotron Radiation Laboratory, University of Science and Technology of China, Hefei 230029, China

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Abstract In applications of solar physics, extreme ultraviolet imaging of solar corona by selecting the He-II ($\lambda = 30.4$ nm) emission line requires high reflectivity multilayer mirrors. Some material combinations were studied to design the mirrors working at a wavelength of 30.4 nm, including SiC/Mg, B₄C/Mg, C/Mg, C/Al, Mo/Si, B₄C/Si, SiC/Si, C/Si, and Sc/Si. Based on optimization of the largest reflectivity and the narrowest width for the multilayer mirror, a SiC/Mg material combination was selected as the mirror and fabricated by a magnetron sputtering system. The layer thicknesses of the SiC/Mg multilayer were measured by an X-ray diffractometer. Reflectivities were then measured on beamline U27 at the National Synchrotron Radiation Laboratory (NSRL) in Hefei, China. At a wavelength of 30.4 nm, the measured reflectivity is as high as 38.0%. Furthermore, a series of annealing experiments were performed to investigate the thermal stability of the SiC/Mg multilayer.

Keywords thin film optics, solar He-II radiation, extreme ultraviolet, multilayer reflective mirror, magnetron sputtering, synchrotron radiation

1 Introduction

In applications of solar physics, the emission lines of Fe-IX ($\lambda = 17.1$ nm), Fe-XII ($\lambda = 19.5$ nm), Fe-XV ($\lambda = 28.4$ nm) and He-II ($\lambda = 30.4$ nm) can be selected as imaging of solar corona [1–9]. Due to the strong absorption of most materials in an extreme ultraviolet (EUV) region, the optical system at normal incidence requires a high reflectivity multilayer mirror. In recent years, the achievements in multilayer technology has enabled the develop-

ment of new instrumentation and led to a number of successful missions such as solar and heliospheric observatory/extreme ultraviolet imaging telescope (SOHO/EIT) and transition region and coronal explorer (TRACE) [1–3]. In this article, some multilayer reflective mirrors were studied for He-II radiation (30.4 nm). Usually, at wavelengths longer than the Si L-absorption edge near 12.4 nm, the multilayer material combinations based on Si are widely used in the 13–20 nm region [10–15]. The Mo/Si multilayer was widely used for its high stability and fairly high reflectivity, especially under the motivation of an EUV lithograph in the integrated circuit industry. However, the reflectivity of a Mo/Si multilayer falls gradually with increasing wavelength. At a wavelength of 30.4 nm, the reflectivity is reduced to about 20%. Therefore, new high-reflectivity multilayer mirrors would have to work at that wavelength. In this paper, reflection performance of some material combinations based on Mg and Si were investigated to design a multilayer at 30.4 nm, including SiC/Mg, B₄C/Mg, Mo/Si, B₄C/Si, SiC/Si, C/Si, and Sc/Si. Based on optimization of the largest reflectivity and the narrowest width, the SiC/Mg material combination was selected to design the high reflectivity multilayer mirrors for He-II radiation. The multilayers were then prepared by using the direct current magnetron sputtering method, and the reflectivities were measured by the reflectometer at the National Synchrotron Radiation Laboratory (NSRL) in Hefei, China.

2 Design of multilayer mirror

In the EUV region, the closeness of the (real part of the) refractive index, coupled with high absorption, makes the reflectivity of a single layer extremely low, according to the Fresnel formula, with magnitude just in the order of 1×10^{-4} . Spiller has proposed that the multilayer film scheme constituted by an absorber and a spacer can

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E-mail: jtzhu@mail.tongji.edu.cn

improve reflectivity in the region, which essentially means enhancement of multiple-beam interference. To get the highest possible reflectivity of the multilayer, the selection of a material combination should satisfy the following requirements [16,17]:

- 1) The difference in the real part of the refraction index (n) between the two materials should be the largest.
- 2) The absorption at the working wavelength, i.e., the imaginary part of refraction index (k), should be low.

In addition, the interface between the two materials should be smooth and sharp with low diffusion. The n - k complex plane is available for the selection of multilayer materials as shown in Fig. 1. The optical constants n and k of the materials used at the wavelength of 30.4 nm were shown on a complex plane. It can be seen that the absorption coefficients k of Mg, Si, and Al are lower, and these materials can be selected as space layers in the design. C, SiC, and B₄C can be used as absorb layer materials, which also have low absorption and a rather larger difference in the real part of refraction index n . In this paper, some material combinations working at the target wavelength, including Si-based and Mg-based combinations, were calculated for periodical multilayers using a conventional Fresnel theoretical method [18]. Figure 2 shows the calculated reflectivities of different material combinations at an incidence angle of 10° for the wavelength, varying with the bi-layer number. Here, the interface between the materials was considered as an ideal condition, i.e., without roughness and diffusion. It can be seen that the reflectivities of Mg-based material combinations are higher than those of Si-based ones. The Mo/Si combination, which is widely used in the EUV region, has the lowest reflectivity at 30.4 nm (only of 25.61%).

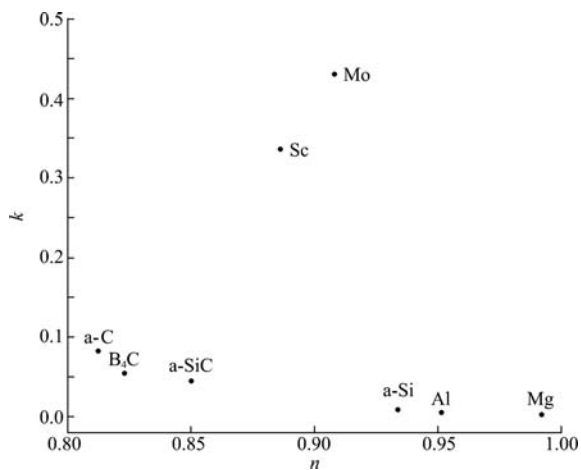


Fig. 1 Optical constant of material at wavelength of 30.4 nm

In high-resolution spectroscopy and imaging experiments, a multilayer reflective mirror is required for the highest possible reflectivity and the smallest possible

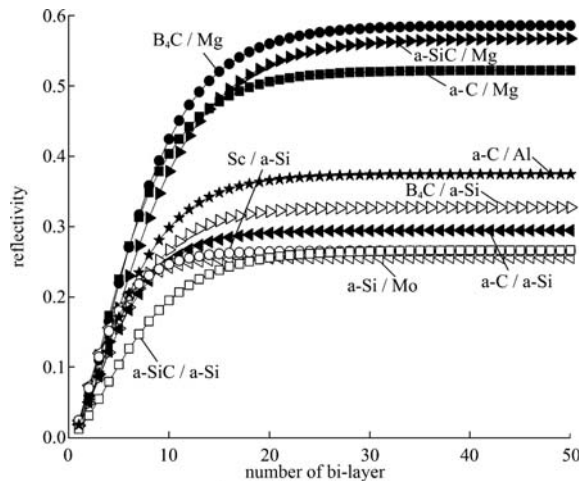


Fig. 2 Reflectivities of all kinds of material combinations at 30.4 nm and incident angle of 10°

spectral bandwidth (full width at half maximum, FWHM). The calculated peak reflectivities and spectral bandwidths at the wavelength of 30.4 nm and incident angle of 10° are listed in Table 1 for various material combinations with 30-pair multilayers. It can be seen that the SiC/Mg combination has a significantly high reflectivity of 56.03% and narrower bandwidth of 1.67 nm, while the Mo/Si multilayer has a lower reflectivity and the largest bandwidth. The material combination SiC/Mg was thus selected as the multilayer reflective mirror working at the wavelength of 30.4 nm.

Table 1 Peak reflectivities and bandwidths (FWHM) at wavelength of 30.4 nm and incident angle of 10° for the 30-pair multilayers shown in Fig. 2

multilayer	layer thickness/nm	reflectivity	$\Delta\lambda$ /nm
SiC/Mg	4.41/11.43	0.5603	1.67
B ₄ C/Mg	4.10/11.75	0.5816	1.83
C/Mg	4.12/11.73	0.5201	2.00
C/Al	4.64/11.93	0.3733	1.83
C/Si	5.34/11.63	0.2941	2.00
SiC/Si	6.23/10.71	0.2648	1.50
B ₄ C/Si	5.93/11.10	0.3267	2.00
Sc/Si	3.32/13.34	0.2653	2.00
Mo/Si	3.03/13.61	0.2561	2.33

3 Preparation and measurement of SiC/Mg multilayer

After design and optimization, the SiC/Mg multilayers were prepared by an ultra-high vacuum direct current magnetron sputtering deposition system (JGP560C6, made in China), which was described in previous article/s [10–15, 17–19]. This system typically reaches a base pressure of about 5×10^{-5} Pa. The working gas is Ar (purity is 99.999%) at the pressure of 0.1 Pa. Deposited multilayers were then measured for quality

control and depositing rate control by using a small angle X-ray diffractometer (XRD, D1 system, Bede Ltd, UK). Using the constant power sputtering mode, the deposition rates of Mg and SiC are 0.17 nm/s and 0.10 nm/s, respectively. Figure 3 shows the XRD measured and fitted results. The period thickness can be calculated from the diffraction peak positions in the measured curve according to the amended Bragg formula. This period thickness is 15.93 nm, which seems a little thicker than the design one (15.84 nm). The fitted data of X-ray diffraction indicates that the thicknesses of Mg and SiC are 11.49 and 4.45 nm respectively [18], which are both thicker than the design ones according to the designed results in Table 1. The value Γ , 0.2791, is the absorber layer thickness ratio of the SiC layer to the period thickness.

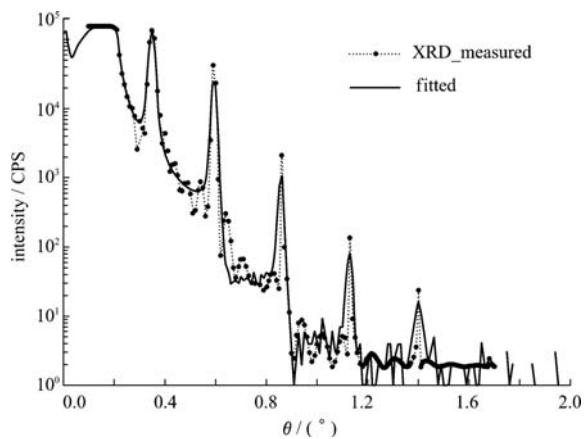


Fig. 3 Small-angle XRD measured and its fitted curve for SiC/Mg multilayer

The reflective performances of the SiC/Mg multilayers were measured by the reflectometer on beam line U27 at the National Synchrotron Radiation Laboratory (NSRL) in Hefei, China. To suppress high harmonics spectra, an aluminum (Al) filter was inserted into the beam path. Reflectivities were measured at the fixed angle in wavelength-scanning mode. Figure 4 shows the measured and fitted results of the SiC/Mg multilayer reflective mirror at the design angle (gazing incident angle of 80°). The fitted data in Fig. 4: $d = 15.986$ nm, $\gamma = 0.2762$, $\sigma(\text{SiC/Mg}) = 1.834$ nm, and $\sigma(\text{Mg/SiC}) = 1.916$ nm. It can be seen that the peak wavelength is 30.57 nm, deviating from the design one (30.40 nm). After changing the measured grazing incident angle of 78° , the peak reflectivity is 38.0% at the wavelength of 30.36 nm, as shown in Fig. 5. These synchrotron radiation measured data were also fitted and the results are shown in Figs. 4 and 5. The fitted period thickness (d) and the thickness ratio (γ) coincide with the XRD fitted values shown in Fig. 3. The fitted data in Fig. 5: $d = 15.9893$ nm, $\gamma =$

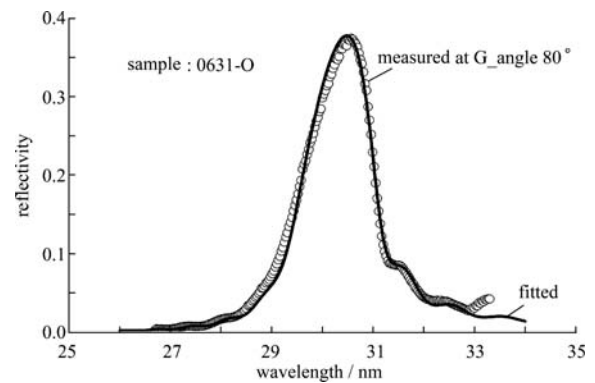


Fig. 4 Reflectivity of SiC/Mg multilayer measured by synchrotron radiation at grazing incident angle of 80° and its fitted data. Peak reflectivity is 37.4% at wavelength of 30.57 nm.

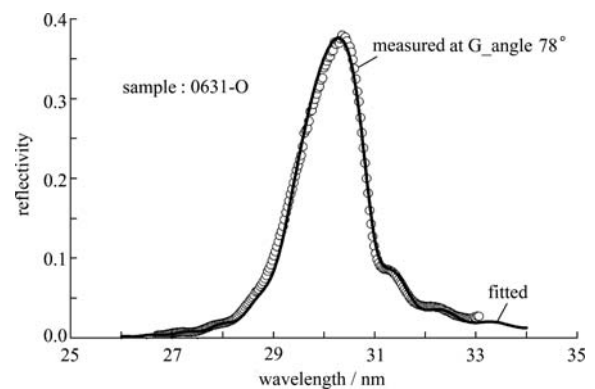


Fig. 5 Reflectivity of SiC/Mg multilayer measured by synchrotron radiation at grazing incident angle of 78° and its fitted data. Peak reflectivity is 38.0% at wavelength of 30.36 nm.

0.2818, $\sigma(\text{SiC/Mg}) = 1.7716$ nm, and $\sigma(\text{Mg/SiC}) = 1.9389$ nm. The fitted results indicate that the roughnesses of SiC_on_Mg interface ($\sigma(\text{SiC/Mg})$) and Mg_on_SiC interface ($\sigma(\text{Mg/SiC})$) are both about 1.8 nm, which leads to a lower measured reflectivity than the theoretical one. The reflectivity of multilayers is expected to be further increased by reducing interface roughness via optimizing preparation techniques. From Fig. 2 and Table 1, the theoretical reflectivity of a Mo/Si multilayer, which is commonly used in EUV region, can only reach 25.6% at the wavelength of 30.4 nm. Therefore, the reflectivity of the SiC/Mg multilayer prepared by current technique conditions is significantly higher than that of a Mo/Si multilayer.

Calculation and experiment have shown that the SiC/Mg periodical multilayer is a very promising reflective mirror near the wavelength of 30.4 nm. But this multilayer has not yet been extensively studied, especially from the point of view of its thermal stability. Since this mirror will work in the space environment,

the thermal stability of an SiC/Mg multilayer is required. A series of annealing experiments were performed in a vacuum chamber at different annealing temperatures for one hour. After annealing, the reflectivities were measured (Fig. 6). It can be seen that the reflectivity decreases significantly with increasing temperature. When the temperature reaches 500°C, no reflectivity is obtained. Using the electron-induced X-ray emission spectra, we studied the interface of the SiC/Mg multilayer before and after annealing. The measurements were performed by Mg-K β and Si-K β , respectively [20]. Both of the measured results show that Mg reacts with Si to form Mg₂Si at the interface of the multilayer. Thus, the barrier layer at the interfaces will be inserted to enhance the thermal stability of the SiC/Mg multilayer.

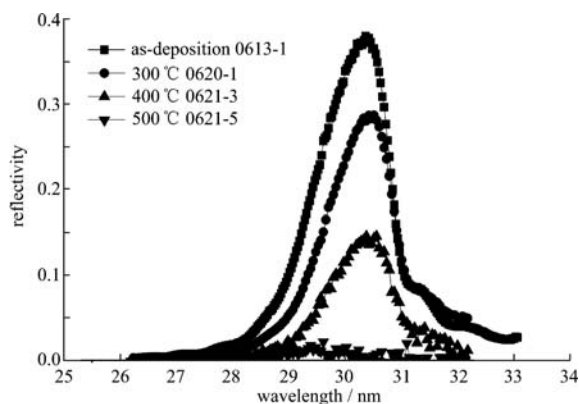


Fig. 6 Measured reflectivities of SiC/Mg multilayer before and after annealing at different temperatures

4 Summary

For the extreme ultraviolet imaging of solar corona by selecting an He-II emission line, a promising SiC/Mg multilayer reflective mirror was designed, prepared and measured. At the grazing incident angle of 78°, the measured reflectivity is 38.0% at the wavelength of 30.4 nm. However, the difference between theoretical reflectivity and measured reflectivity indicates significant roughness on the multilayer interface. The annealing experiment suggests that the thermal stability is weak. Further investigation on the design and fabrication technology is required.

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