

Mo/Si multilayers used for the EUV normal incidence solar telescope

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This paper first reviews an EUV normal incidence solar telescope that we have developed in our lab. The telescope is composed of four EUV telescopes and the operation wavelengths are 13.0 nm, 17.1 nm, 19.5 nm, and 30.4 nm. These four wavelengths, fundamental to the research of the solar activity and the atmosphere dynamics, are always chosen by the EUV normal incidence solar telescope. In the EUV region, almost all materials have strong absorption, so optics used in this region must be coated by the multilayer. The Mo/Si multilayers used for the EUV normal incidence solar telescope are designed and fabricated by the magnetron sputtering coating machine. The characteristics of these multilayers, such as reflectivity and thermal stability at wavelengths of 13.0 nm, 17.1 nm, 19.5 nm and 30.4 nm, are also described. All the multilayers were measured by a hard X-ray diffractometer (XRD) and an EUV/soft X-ray reflectometer (EXRR) before and after heating (in a vacuum chamber) at 100°C for 24 hours and at 200°C for 1 hour and 4 hours. The results show that Mo/Si multilayers have high reflectivity at 13.0 nm, 17.1 nm, and 19.5 nm but low at 30.4 nm. We found no change in the reflectivity and center wavelength of these multilayers by comparing the reflectivity curves before and after heating. This suggests the thermal stability of Mo/Si multilayers may meet our requirement in future solar observation missions.

EUV, solar telescope, multilayer, reflectivity, thermal stability

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1 Introduction

Space weather is an emerging field of space science. The activities of the sun such as solar flares, solar active regions, coronal holes and coronal mass ejections have tremendous influence on the earth's environment. Some of the emission lines from the sun belong to the Extreme Ultra-violet (EUV) region, and the emission lines at 13.0 nm, 17.1 nm, 19.5 nm, and 30.4 nm are fundamental for understanding the solar activities and atmosphere dynamics. The EUV solar telescope is one of the most important instruments to observe the solar dynamics [1–3]. While almost all the materials

have strong absorption and have almost no reflectivity at these four wavelengths, the optics used in this region must be coated with multilayers to get high reflectivity. The development of multilayer coating technology paves the way to the development of normal incident optical instrument in the EUV spectral region. Normal incident telescopes coated with multilayer mirrors have been used in a variety of missions, such as SOHO/EIT, TRACE, SELENE and SDO-AIA [4–7]. We have developed a space EUV normal incidence telescope equipped with multilayer mirrors to get high-resolution solar EUV images in the space.

Silicon is an attractive and widely used material in the EUV multilayer mirrors, due to its low absorption at the wavelengths longer than Si L-absorption edge and the high stability between silicon and other materials [8,9]. The

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Mo/Si multilayers for a normal incidence solar telescope are designed, and the deposition, reflectivity and thermal stability of these multilayers are also described.

2 Review on the EUV normal incidence solar telescope

The EUV normal incidence solar telescope to get high-resolution solar EUV images in the space, composed of four EUV telescopes, has been developed in our lab [10]. Each telescope consists of a piece of aluminum filter, a normal incidence Cassegrain optics coated with multilayer film, a secondary mirror controlling unit, an EUV detector, a mechanical structure and a vacuum chamber. See Figure 1 for its picture. Its specifications are shown in Table 1. When the solar radiation enters the telescope, wavelength of the radiation over 60 nm is blocked by the aluminum filter. The residual radiation is focused on the EUV CCD detector by the normal incident optics coated with multilayer, and the EUV solar image is obtained.

3 Multilayer designs

In the EUV region, the number of potential spacer materials falls dramatically due to the strong absorption. Fortunately, silicon has a very low absorption for wavelengths longer than 12.3 nm (L edge of Si) and becomes a suitable spacer material [9]. The optical constants for silicon in the EUV region is shown in Figure 2.

In order to get the highest optical contrast in the EUV region, we chose molybdenum to be paired with silicon. The multilayer mirrors with Si and Mo for the normal incident solar telescope at 13.0 nm, 17.1 nm, 19.5 nm and 30.4 nm were designed, and the reflectivity of these multilayer

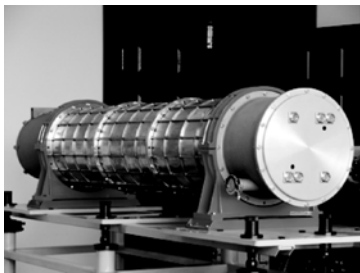


Figure 1 Space EUV solar telescope.

Table 1 The specifications of the space EUV solar telescope

Items	Parameters
Operating wavelength (nm)	13.0, 17.1, 19.5, 30.4
Field of view	8.5'×8.5'
Angular resolution	0.8"
Focal length (mm)	7040

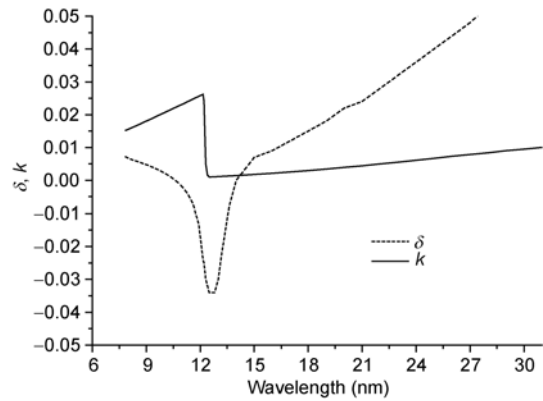


Figure 2 Optical constants for Si in the EUV region.

mirrors was calculated. The optimized results are shown in Table 2. The calculated reflectivity curves of the Mo/Si multilayer at 13.0 nm, 17.1 nm, 19.5 nm and 30.4 nm are shown in Figure 3.

4 Multilayer coating

The Mo/Si multilayers were deposited onto (100) single silicon wafers by the magnetron sputtering coating machine. There are 2 radio frequency (RF) targets and 2 direct current (DC) targets in the machine and the angle of the sputtering guns (targets) can be changed from 0 to 25° according to different diameters of the mirror for better uniformity. Figure 4 is the position of the sputtering guns in the vacuum chamber. The basic vacuum pressure is lower to 8×10^{-4} Pa, the operating pressure is 1.0×10^{-1} Pa and argon (99.99%) is used as the process gas. The magnetron sputtering sources used for multilayer deposition are planar 4 inches diameter disks. The powers applied to targets and the deposition rate of the materials are listed in Table 3.

5 X-ray and EUV reflectivity

All multilayers we deposited were measured by a hard

Table 2 Optimized results of the Mo/Si multilayers

$\lambda_{\max}$ (nm)	d (nm)	Γ_{Si}	N	$R_{\max}$ (%)
13.0	6.64	0.6	40	73.3
17.1	8.9	0.6	40	57.6
19.5	10.2	0.7	40	48.1
30.4	16.38	0.8	40	22.8

Table 3 Powers applied to targets and deposition rate

Material	Power	Deposition rate (nm s^{-1})
Si	300 W (RF)	0.131
Mo	300 mA (DC)	0.134

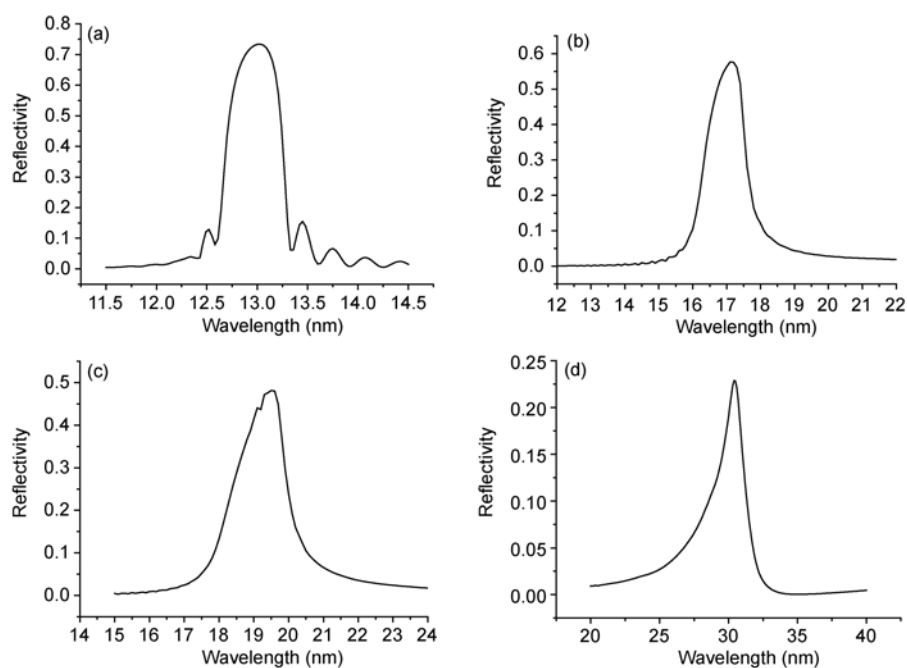


Figure 3 Calculated reflectivity of the optimized Mo/Si multilayers at 13.0 nm (a), 17.1 nm (b), 19.5 nm (c), and 30.4 nm (d).

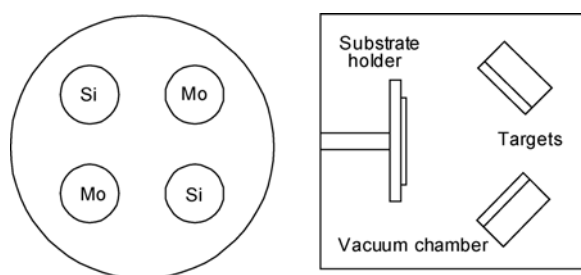


Figure 4 Position of the sputtering guns.

X-ray diffractometer (XRD) which uses Cu $K\alpha$ line ($\lambda=0.154$ nm) and the angle resolution of XRD is 0.005° . The EUV reflectance of these multilayers was measured by an EUV/soft X-ray reflectometer (EXRR) near the normal incidence (3°). The measured reflectance repeatability and wavelength repeatability of EXRR is $\pm 1\%$ and ± 0.04 nm respectively [10,11]. Figures 5 and 6 are the measured graphs of small angle X-ray diffraction (SAXRD) and EXRR. The measured and analytical results are shown in Table 4.

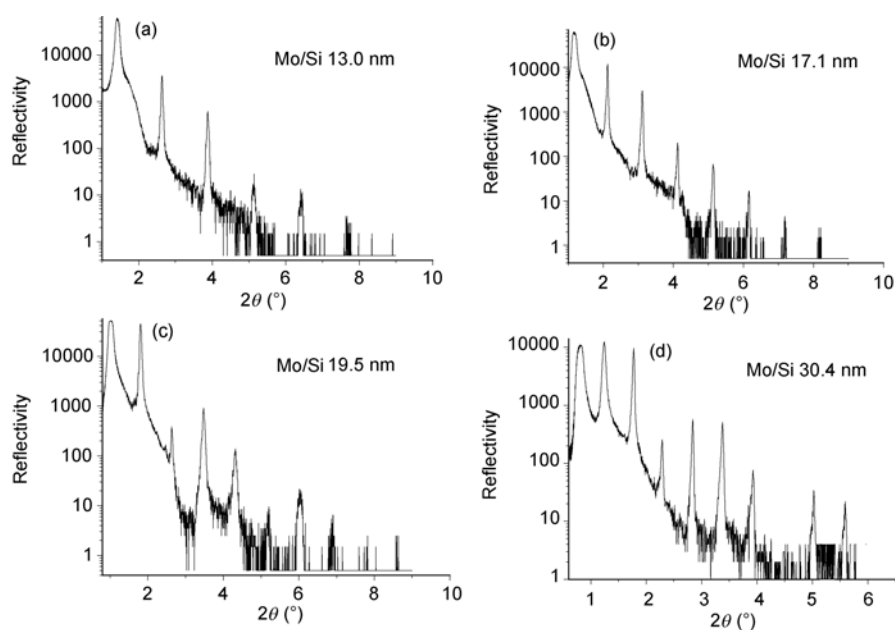


Figure 5 Small angle X-ray diffraction diagram of the Mo/Si multilayers at 13.0 nm (a), 17.1 nm (b), 19.5 nm (c) and 30.4 nm (d).

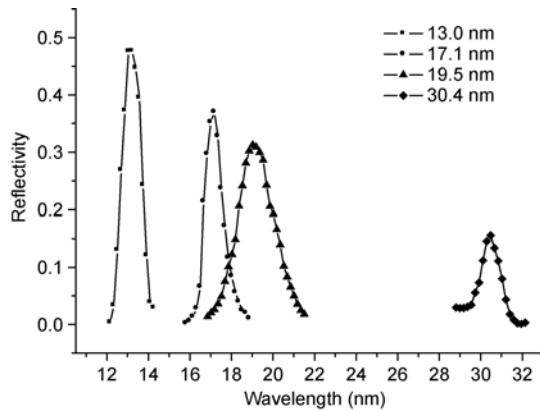


Figure 6 Measured EUV reflectivity of the Mo/Si multilayers at 13.0 nm, 17.1 nm, 19.5 nm and 30.4 nm.

Table 4 Structure parameters determined from XRD and EXRR

λ_{design} (nm)	d (nm)	Γ_{Si}	σ_{rms} (nm)	R_{max} (%)	λ_{max} (nm)
13.0	6.75	0.59	1.23	47.6	13.15
17.1	9.1	0.62	1.40	37.1	17.14
19.5	10.23	0.68	1.20	31.1	19.10
30.4	16.48	0.82	1.22	15.6	30.45

6 Thermal stability

The solar telescope we designed is planned to be mounted

on the polar-orbiting satellite [12], which demands a high temperature environment to the multilayer mirrors. So the long-term thermal stability is one of the most important characteristics of the multilayer used for the solar telescope. For testing the thermal stability of the multilayer, the multilayers were placed in an vacuum chamber at 100°C (holding for 24 hour) and 200°C (holding for 1 hour and then 4 hours). During the heating process, the pressure of the vacuum chamber was kept at 8.0×10^{-4} Pa. After heating, all the samples were measured by EXRR. It is obvious, shown in Figure 7, that the reflectivity and center wavelength of all Mo/Si multilayers before and after heating at 100°C and 200°C experienced almost no change compared with that before heating.

Optical characteristics of Mo/Si multilayer mirrors, such as reflectivity and center wavelength, depend on the structure of the interfaces. Former studies have revealed that Mo/Si multilayer consists of amorphous Si layers, crystalline Mo layers and thin amorphous alloy layers at each Mo/Si interface. The change of interfaces results from further intermixing and formation of silicide will influence the reflectivity and center wavelength of Mo/Si multilayer mirrors, and the change can be deduced from the SAXRD. The observation of fewer diffraction orders indicated that further intermixing occurred at interfaces. Contraction of the multilayer period revealed the formation of silicide from the pure layers, because the density of silicide is higher than pure Mo and Si. Figure 8 is the measured SAXRD of Mo/Si

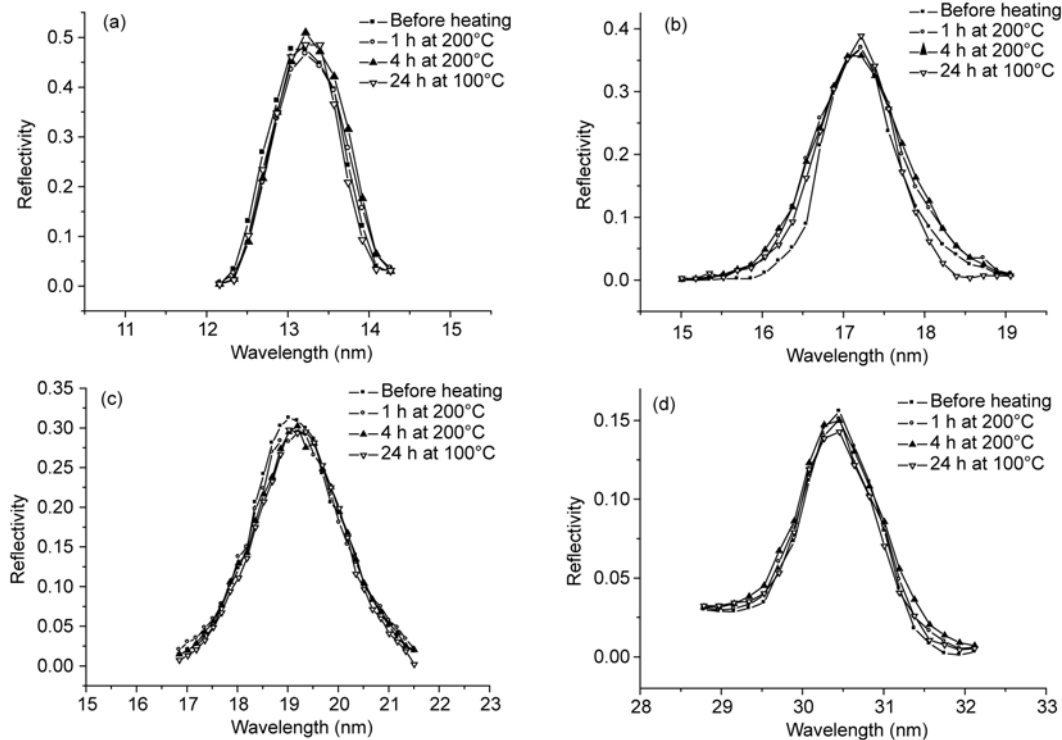


Figure 7 Comparison of the measured EUV reflectivity of Mo/Si multilayer, before and after heating, 100°C for 24 h, 200°C for 1 and 4 h, at 13.0 nm (a), 17.1 nm (b), 19.5 nm (c) and 30.4 nm (d).

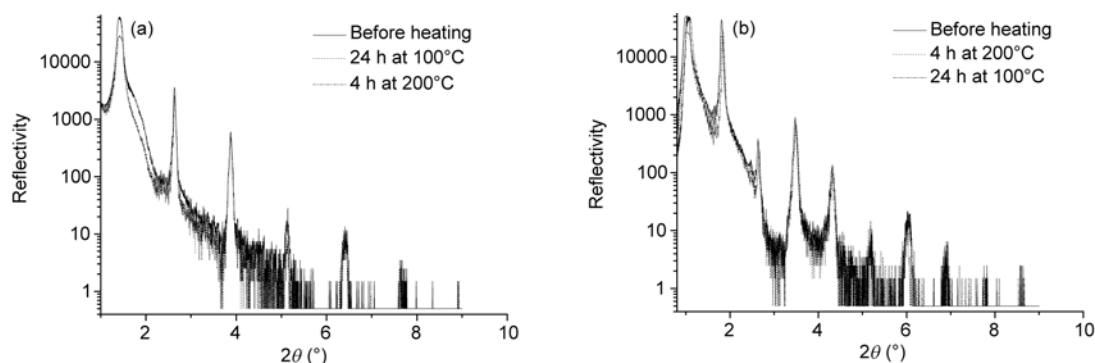


Figure 8 SAXRD of the Mo/Si multilayers at 13.0 nm (a) and 19.5 nm (b) before and after heating at 100°C and 200°C for 24 and 4 h.

multilayers at 13.0 nm and 19.5 nm before and after heating at 100°C and 200°C for 24 hours and 4 hours respectively. The SAXRD of multilayers at 17.1 nm and 30.4 nm is not shown here, due to the same results compared with those at 13.0 nm and 19.5 nm.

However, almost no differences, before and after heating, can be observed from Figure 8, indicating no significant change at interfaces. In addition, the interdiffusion and formation of silicide occur when the energy is higher than the activation energy, about 2 eV. The formation temperature of silicide is above 200°C and the formation temperature of crystalline MoSi₂ even higher up to 525°C, suggesting the long-term thermal stability at low temperatures (below 100°C) is consistent with our experiment results [13–16]. The maximum temperature of multilayer mirrors in the solar telescope during future missions will be approximately 100°C, so that the thermal stability of Mo/Si multilayer could well meet the requirements of solar observation missions in future.

7 Summary

The research on the Mo/Si multilayer used for the EUV normal incidence solar telescope is described in the paper. The test results show that Mo/Si multilayer fits the solar observation mission for its high reflectivity at 13.0 nm, 17.1 nm and 19.5 nm and its long term thermal stability which is thermally stable up to 200°C far beyond the requirement.

However, we also find that the Mo/Si multilayer has low reflectivity at 30.4 nm. So further research is required to find new materials with high reflectivity (at 30.4 nm) and also long-term thermal stability.

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