# Interface roughness, surface roughness and soft X-ray reflectivity of Mo/Si multilayers with different layer number

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A series of Mo/Si multilayers with the same periodic length and different periodic number were prepared by magnetron sputtering, whose top layers were respectively Mo layer and Si layer. Periodic length and interface roughness of Mo/Si multilayers were determined by small angle X-ray diffraction (SAXRD). Surface roughness change curve of Mo/Si multilayer with increasing layer number was studied by atomic force microscope (AFM). Soft X-ray reflectivity of Mo/Si multilayers was measured in National Synchrotron Radiation Laboratory (NSRL). Theoretical and experimental results show that the soft X-ray reflectivity of Mo/Si multilayer is mainly determined by periodic number and interface roughness, surface roughness has little effect on reflectivity.

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Molybdenum/silicon (Mo/Si) multilayers have been developed in the last decade for their wide range of applications from astrophysics[1−4] to lithography[5,6]. Especially in the soft X-ray wavelength around 13 nm, Mo/Si multilayers with high reflectivity have achieved applicable level for the extreme ultraviolet lithography (EUVL)[7]. Soft X-ray reflectivity of multilayers is determined by interface roughness and optical contrast[8,9]. When the film layer is ultrathin, effect of interface roughness is not neglected. Interface roughness is an average concept, it is equal to the root mean square deviation of interface atoms with respect to a smooth interface, which can be achieved by fitting curve of small angle X-ray diffraction (SAXRD)[10]. However, the incidence X-ray beam permeates through surface layer of multilayers firstly, surface roughness of multilayer may also have an important effect on reflectivity of multilayers[11]. In this paper, effects of layer number on surface roughness, interface roughness and soft X-ray reflectivity of Mo/Si multilayers with Mo and Si top layer are respectively studied. The aim is to investigate the relation among surface roughness, interface roughness, soft X-ray reflectivity and number of layers.

The Mo/Si multilayers were designed at center wavelength of 13.5 nm, normal incidence angle of 15°. The periodic length $d$ was 7.3 nm. The ratio of the layer thickness $\Gamma(d_{\mathrm{Mo}}/d)$ was 0.5. The number of layers changed from 20 to 121.

The Mo/Si multilayer was fabricated by a binary target RF/DC magnetron sputtering system. The deposition chamber was evacuated to $10^{-6}$ Torr with rotary pump and molecular pump. K9 glass wafers (3 mm in thickness and 30 mm in diameter, roughness 0.8 nm) were used as substrates. Molybdenum (99.99%) and silicon (99.99%) of the same size (78 mm in diameter and 3 mm in thickness) were used as the targets. The distance between targets and the substrate was 150 mm. The substrate was rotated at 8 rps in order to achieve homogeneous deposition of molybdenum and silicon. The Mo target was sputtered at 120-W power by DC magnetron sputtering and Si target was sputtered at 300 W power by RF magnetron sputtering, which resulted in Mo and Si deposition rates of 0.15 and 0.14 nm/s respectively. The silicon layer was firstly deposited on a K9 glass wafer and then an molybdenum layer was deposited on top. This procedure was repeated for appropriate times in order to obtain multilayers with various numbers of layers. Depending on whether the number of the layers is even or odd, these samples are called $[\mathrm{Mo/Si}]_n$ or $\mathrm{Si}[\mathrm{Mo/Si}]_n$, so that we can investigate Mo/Si multilayers with Mo top layer or Si top layer. '$n$' represents the number of bilayer pairs of Mo/Si multilayers. In this paper, $n = 10$, 20, 30, 40, 50, 60. As an example, the numbers of layers of $[\mathrm{Mo/Si}]_{30}$ and $\mathrm{Si}[\mathrm{Mo/Si}]_{30}$ multilayers are respectively 60 and 61, the top layers of $[\mathrm{Mo/Si}]_{30}$ and $\mathrm{Si}[\mathrm{Mo/Si}]_{30}$ multilayers are respectively Mo and Si.

Periodic length was confirmed using XRD equipment (D/max-rA type). SAXRD measurement was performed with the incidence angles from 0.5° to 7°, Cu $K_\alpha$ (0.154 nm) . The Periodic length and interface roughness were calculated by fitting of SAXRD curve[10]. Surface roughness of Mo/Si multilayers was characterized by atomic force microscopy (AFM) (model: Sekio S II type), measuring area is 500 × 500 (nm). AFM measurement was performed in tapping mode. We chose the average value of five measureing points as surface roughness for every sample.

The near-normal-incidence reflectivity of the Mo/Si multilayer was measured using soft X-ray in National Synchrotron Radiation Laboratory (NSRL), University of Science and Technology of China. The measurement was carried out under $5.0 \times 10^{-8}$ Torr base pressure at near-normal-incidence angle of 15°.

SAXRD patterns of the $[\mathrm{Mo/Si}]_n$ and $\mathrm{Si}[\mathrm{Mo/Si}]_n$ multilayers series are shown in Fig. 1. Their positions of diffraction peaks are basically the same and the calculated periodic length is summarized in Table 1. It is found that periodic length of each multilayer is approximately equal, which suggests our coating process is stable.

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**Table 1. Periodic Length and Interface Roughness of Mo/Si Multilayers**

| | Periodic Number | 10 | 20 | 30 | 40 | 50 | 60 |
|---|---|---|---|---|---|---|---|
| $[\mathrm{Mo/Si}]_n$ | Periodic Length (nm) | 7.32 | 7.29 | 7.31 | 7.35 | 7.33 | 7.36 |
| | Interface Roughness (nm) | 0.37 | 0.44 | 0.64 | 0.66 | 0.72 | 0.85 |
| $\mathrm{Si}[\mathrm{Mo/Si}]_n$ | Periodic Length (nm) | 7.34 | 7.31 | 7.35 | 7.26 | 7.33 | 7.29 |
| | Interface Roughness (nm) | 0.62 | 0.65 | 0.84 | 0.84 | 1.02 | 1.14 |

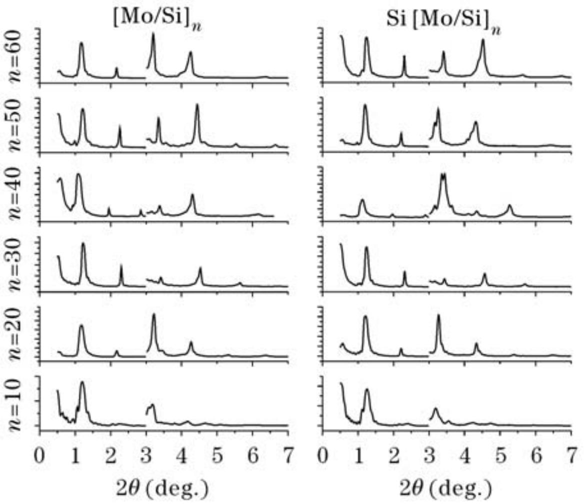

Fig. 1. XRD pattern of $[\mathrm{Mo/Si}]_n$ and $\mathrm{Si}[\mathrm{Mo/Si}]_n$ multilayers.

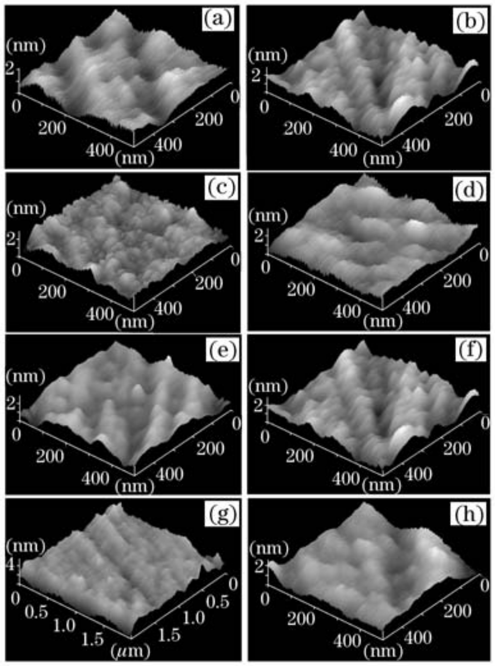

Fig. 2. AFM images of Mo/Si multilayers. (a) $[\mathrm{Mo/Si}]_{10}$; (b) $[\mathrm{Mo/Si}]_{20}$; (c) $[\mathrm{Mo/Si}]_{40}$; (d) $[\mathrm{Mo/Si}]_{60}$; (e) $\mathrm{Si}[\mathrm{Mo/Si}]_{10}$; (f) $\mathrm{Si}[\mathrm{Mo/Si}]_{20}$; (g) $\mathrm{Si}[\mathrm{Mo/Si}]_{40}$; (h) $\mathrm{Si}[\mathrm{Mo/Si}]_{50}$.

AFM can be used in surface morphology analysis of multilayers. Figure 2 shows AFM images of some multilayer samples. Form Fig. 2 it can be seen that surface morphology changes drastically with increasing number of layers which also shows the change of surface roughness. Figure 3 shows the surface roughness and interface roughness of various multilayer films.

Obviously, surface roughness of the $\mathrm{Si}[\mathrm{Mo/Si}]_n$ series is higher than the $[\mathrm{Mo/Si}]_n$ series, surface roughness of Si film layer is higher than Mo film layer in the multilayers. Their change curve of surface roughness is basically the same as that the roughness increased drastically at the beginning and reached a maximum and then drastically decreased. Interface roughness change curve of $\mathrm{Si}[\mathrm{Mo/Si}]_n$ series and $[\mathrm{Mo/Si}]_n$ series is also the same, they increase with increasing number of layer.

Soft X-ray reflectivity of $[\mathrm{Mo/Si}]_n$ and $\mathrm{Si}[\mathrm{Mo/Si}]_n$ multilayers is shown in Fig. 4. The center-wavelengths of various multilayers are basically consistent, which implies again that periodic length of Mo/Si multilayers is nearly the same.

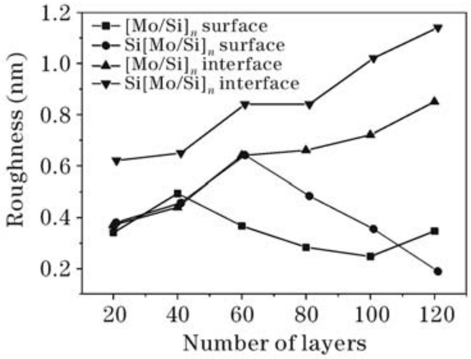

Fig. 3. Curve of roughness versus number of layers of Mo/Si multilayers.

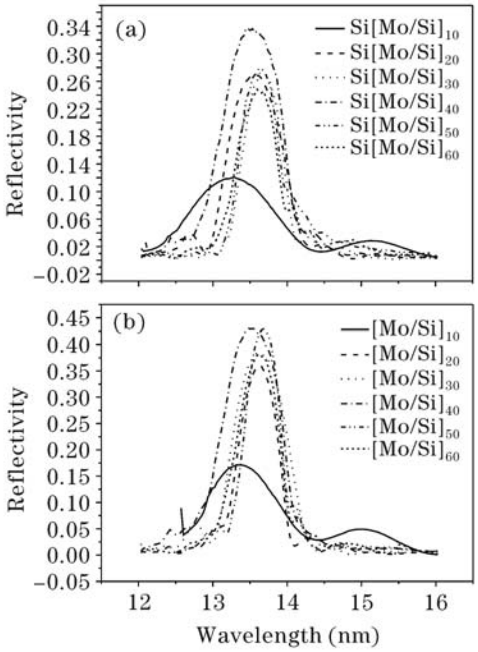

Fig. 4. Reflectivity curve of Mo/Si multilayers. (a) $\mathrm{Si}[\mathrm{Mo/Si}]_n$ series; (b) $[\mathrm{Mo/Si}]_n$ series.

The graph of theoretical peak reflectivity and practical peak reflectivity versus number of layers of [Mo/Si]$_n$ and Si[Mo/Si]$_n$ multilayers is shown in Fig. 5. As Fig. 5 shows, the practical peak reflectivity of multilayers with Mo top layer is higher than that of multilayers with Si top layer, it conforms to theory. Practical peak reflectivity increases quickly with increasing number of layers at the beginning and reaches a maximum at 80 layers and then decreases slowly. But according to theory, peak reflectivity should be invariable after 80 layers. Why is change curve of theoretical peak reflectivity and practical peak reflectivity different? It can be explained with change of interface roughness. Firtly, when to calculate theoretical peak reflectivity, interface roughness is assumed to be zero. However, practical interface roughness increases with increasing number of layer. When the number of layer is over 80, the contribution of number of layer is almost zero, but contribution of interface roughness is negative, A combination of two factors resulted in that reflectivity of Mo/Si multilayers increases at first and then decreases.

Effect of surface roughness on reflectivity of Mo/Si multilayers is small. If this effect is more stronger, reflectivity should reduce with increasing surface roughness, they should be in inverse proportion. In fact, from Figs. 3 and 5, surface roughness and peak reflectivity increase firstly and then decrease, they just appear to be in direct proportion, which shows that surface roughness has little effect on reflectivity.

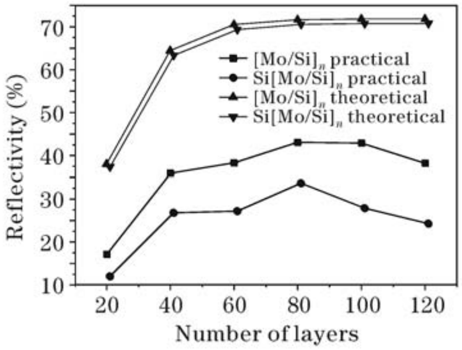

Fig. 5. Curve of peak reflectivity versus number of layers of Mo/Si multilayers.

In conclusion, [Mo/Si]$_n$ and Si[Mo/Si]$_n$ multilayers were prepared by binary target RF/DC magnetron sputtering. Surface roughness of Mo/Si multilayers whose top layer was Mo layer was comparatively smaller than those whose top layers was Si. The surface roughness and peak reflectivity of the Mo/Si multilayers increase firstly and then decrease with increasing number of layers. The interface roughness of the Mo/Si multilayers increases with increasing number of layers. Number of layer and interface roughness have the main effect on reflectivity of multilayers, effect of surface roughness is small.

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