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# Fabrication of Mo/Al multilayer films for a wavelength of 18.5 nm

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This paper reports the fabrication and evaluation of Mo/Al and Mo/Si multilayer films (MLs) for a wavelength of 18.5 nm. Calculated reflectivities of Mo/Al MLs at an incident angle of 10° were about 7% higher than those of Mo/Si MLs. MLs were fabricated using an RF-magnetron sputtering deposition system. The measured reflectivity of Mo/Al MLs was 33.5%. The cause of the decreasing reflectivity was supposed to be the surface and interfacial roughness. In the surface observation utilizing atomic force microscopy, the surface roughness of Mo/Al MLs was dominated by the Al layer. Therefore, the conditions for fabricating Al films were optimized.

**Keywords: Mo/Al; multilayers; reflectivity; soft X-rays.**

## 1. Introduction

Recently, multilayer films (MLs) have been widely studied for developing the optical elements of lasers (London *et al.*, 1989), lithography (Kinoshita *et al.*, 1989) and microscopes (Trail & Byer, 1989) for the extreme UV and soft X-ray regions. They have also been studied as the optical elements for making good use of synchrotron radiation beamlines. However, there are insufficient reflectivity data between 16 and 21 nm, so we have studied MLs applicable to wavelengths in this range.

The absorption for the materials is the problem in this wavelength region. As a light material of the ML we chose aluminium, which has a small extinction coefficient at the longer wavelength of 17.0 nm at the *L*-edge. To achieve a high reflectivity at an incident angle of 10°, molybdenum was chosen as a combination material in view of its optical constants. We designed the ML at the peak wavelength of 18.5 nm in order to obtain a sufficient integrated reflectivity, and have fabricated and evaluated the MLs.

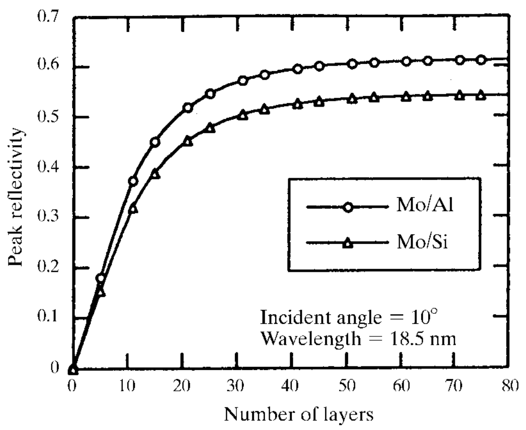


**Figure 1**
Calculated peak reflectivities of Mo/Al (circles) and Mo/Si (triangles) MLs at a wavelength of 18.5 nm *versus* the numbers of layers.

## 2. Experiment

### 2.1. *Design of the MLs*

The MLs have been designed using optical constants and the Fresnel equation (Underwood & Barbee, 1981). Mo/Al MLs with various numbers of layers have been designed at the incident angle of 10° at a peak wavelength of 18.5 nm. Fig. 1 shows the relation between the calculated near-normal-incidence reflectivities and the number of layers for Mo/Al and Mo/Si MLs. The peak reflectivity almost saturates for greater than 40 layers. The saturated reflectivity of Mo/Al MLs was about 7% higher than that of Mo/Si MLs. From the saturation of the calculated reflectivity, it was decided to fabricate the MLs with 41 layers. The periodic length ($d$) and the ratio of the film thickness $\Gamma$ (= $d_{Mo}/d$) for Mo/Al MLs were 9.54 nm and 0.29, respectively, and those for Mo/Si ML were 9.80 nm and 0.30, respectively.

### 2.2. *Fabrication and evaluation*

Mo/Al and Mo/Si MLs were prepared on silicon wafers and float-glass substrates utilizing an RF-magnetron sputtering deposition system. The deposition chamber was pumped down to the base pressure of $3.8 \times 10^{-5}$ Pa. The purity of the target materials was 5 N. During deposition, the Si substrate and its holder were planetary rotated at 10 r.p.m. The distance between the targets and the substrate was 185 mm. The RF power was kept at 100 ± 0.5 W. We had fabricated Mo/Al MLs under Ar gas pressure from $7.5 \times 10^{-2}$ to $2.3 \times 10^{-1}$ Pa, and had obtained the optimum condition of $7.5 \times 10^{-2}$ Pa from X-ray diffraction (XRD) patterns of the MLs. The deposition rates of Mo, Al and Si films were 2.34, 2.52 and 0.78 nm min$^{-1}$, respectively. The thickness of each layer was controlled by the deposition time.

The periodic structures of fabricated films were analysed using Auger electron spectroscopy (AES) and XRD. Small-angle XRD was measured by the Cu $K\alpha$ line at a wavelength of 0.154 nm. The measurement of surface roughness was carried out using atomic force microscopy (AFM). The near-normal-incidence reflectivities

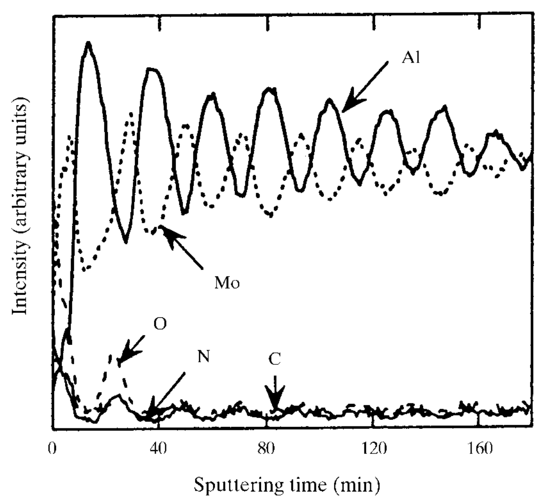


**Figure 2**
AES depth profile analysis of the Mo/Al ML.

of the MLs were measured using the soft X-ray reflectometer with a laser-produced-plasma X-ray source (Nakayama *et al.*, 1990).

## 3. Results and discussion

### 3.1. *Evaluation of periodic structures*

Fig. 2 shows the AES depth profile of an Mo/Al ML. Each spectrum of Mo and Al shows the oscillation in reverse phase during a sputtering time of 180 min. The intensity of the oxygen spectrum increased according to the decrease of the Al spectrum. For the second peak of the Mo spectrum and the first peak of the oxygen spectrum, the intensity of the Mo and oxygen spectra began to increase at the same time, and the peak position of Mo was slightly shifted to the right of the peak position of oxygen. These facts indicated that the upper part of the Mo layer underneath the Al layer near the top layer was oxidized.

Fig. 3 shows small-angle XRD patterns of Mo/Al (solid line) and Mo/Si MLs (dashed line). The periodic Bragg peak of the Mo/Al ML was observed. From these AES and XRD results, the periodic structure of Mo/Al ML was confirmed.

### 3.2. *Roughness*

We compared the interfacial and surface roughness of the Mo/Al ML with that of the Mo/Si ML using XRD and AFM. The fifth Bragg peak of the Mo/Al ML and the eighth peak of the Mo/Si ML are shown in Fig. 3.

The decrease in small-angle reflectivity (and also near-normal incidence) due to the interfacial roughness is given by the square of the Debye–Waller (DW) factor,

$$\mathrm{DW}^2 = \left\{\exp[-2(2\pi\sigma\sin\theta/\lambda)^2]\right\}^2,$$

where $\sigma$ is the roughness (r.m.s.) and $\theta$ is the grazing angle of incident X-rays. The DW factor shows that the effect of the interfacial roughness on the reflectivity increases as the order of the Bragg peak of the ML increases. From this result, the interfacial roughness of the Mo/Al ML was larger than that of the Mo/Si ML.

Fig. 4 shows AFM surface images of (*a*) Mo/Al and (*b*) Mo/Si MLs in a 500 nm × 500 nm area. The surface of the Mo/Al ML was covered with grains of about 100 nm in diameter. However, such grains were not observed and many small projections existed in Mo/Si MLs. The surface roughness of Mo/Al MLs was 0.6 nm (r.m.s.) while the roughness of Mo/Si MLs was only 0.13 nm (r.m.s.). From the results of the surface observation of Al and Si single layers using AFM, the difference between Mo/Al and Mo/Si MLs surface images is attributed to the difference of the surface roughness of Al and Si layers.

### 3.3. *Near-normal-incidence reflectivity*

The near-normal-incidence reflectivities of Mo/Al and Mo/Si MLs were measured with a soft X-ray reflectometer. Fig. 5 shows

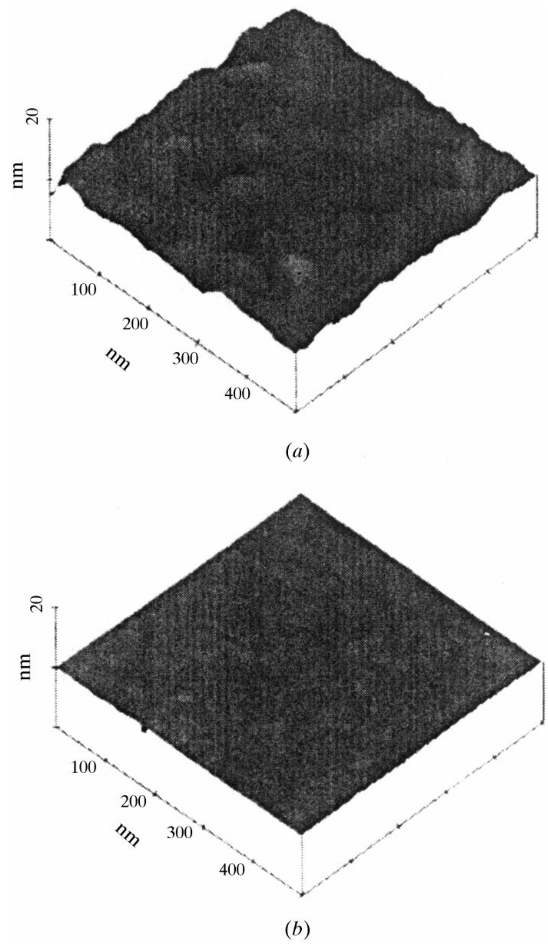


**Figure 4**
AFM surface images of (*a*) Mo/Al and (*b*) Mo/Si MLs in a 500 nm × 500 nm area.

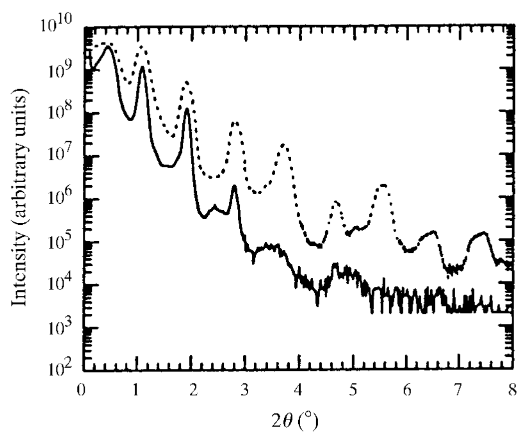


**Figure 3**
Small-angle X-ray diffraction patterns of Mo/Al and Mo/Si MLs (solid line: Mo/Al ML; dashed line: Mo/Si ML).

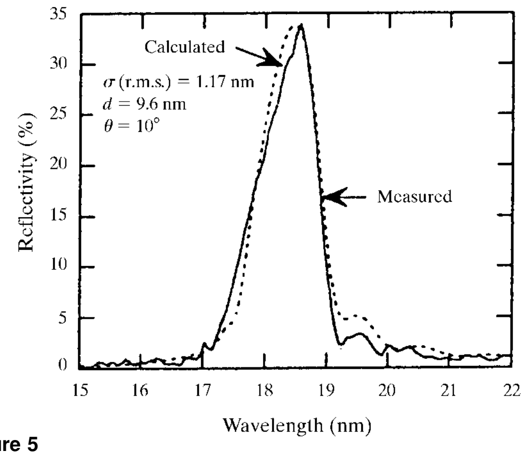


**Figure 5**
Soft X-ray reflectivity at an incident angle of 10° of the Mo/Al ML and the calculated curve (solid line: measured; dashed line: calculated).

**Table 1**
Near-normal-incidence reflectivities of Mo/Al and Mo/Si MLs and the roughnesses (r.m.s.) estimated by their reflectivities.

| ML 41 layers | Peak wavelength (nm) | Calculated reflectivity for ideal structure at incident angle of 10° (%) | Near-normal-incident reflectivity at incident angle of 10° (%) | Roughness (nm) (r.m.s.) calculated by the reflectivity |
|---|---|---|---|---|
| Mo/Al | 18.5 | 59.6 | 33.5 | 1.17 |
| Mo/Si | 17.8 | 52.4 | 36.0 | 0.99 |

the measured (solid line) and fitting curves (dashed line) of the reflectivity of Mo/Al MLs. The measured reflectivity of Mo/Al MLs was 33.5%. The fitting curve was calculated using parameters of the roughness of 1.17 nm (r.m.s.) and the periodic length of 9.6 nm (r.m.s.). The cause for decreasing the near-normal-incident reflectivity is the roughness of the Mo/Al ML. Table 1 shows the peak wavelength, the calculated reflectivities for ideal structures, measured reflectivities and the roughness estimated by the measurement of the reflectivities of Mo/Al and Mo/Si MLs.

There is a difference of more than a factor of two between the interfacial roughness of the MLs estimated by the reflectivity and surface roughness measured by AFM. As shown in the AFM surface profile of the Mo/Al ML (Fig. 4*a*), the ML does not duplicate the surface profile of the Si wafer substrate. It is probable that the roughness in the interface of the ML is greater than that of the surface. Another reason is the difference of the spatial frequencies of roughness affected to the reflectivity and that measured by AFM. Adapting the discussion of ML roughness by Windt *et al.* (1994) to the wavelength of 18.5 nm, the spatial frequency affecting the reflectivities is about 1–50 $\mu m^{-1}$; however, the spatial frequency of roughness of our AFM measurement is about 10–500 $\mu m^{-1}$. If the surface is fractal-like, the power spectrum density of the surface height decreases with the increase in spatial frequency. Another reason is the possibility of a correlated roughness (Windt *et al.*, 1994). If there is a correlated roughness in the ML interface, the X-ray scattered into a non-specular direction is enhanced and the reduction of reflectivity is greater than that estimated by the surface roughness.

The surface image of the Mo/Al ML was similar to that of Al thin film from the results of AFM surface observations. We supposed that the Al layer dominated the roughness of Mo/Al MLs. Therefore we tried to improve the roughness of Al thin film to obtain higher reflectivity in the Mo/Al ML. Al thin films of 34.0 nm thickness were fabricated under different conditions and were observed using AFM. For 80 W and 22.5 r.p.m. the surface roughness was improved from 3.30 nm (r.m.s.) to 1.79 nm (r.m.s.).

## 4. Conclusions

Mo/Al MLs were fabricated using an RF-magnetron sputtering system and evaluated by measurements of AES, XRD and the near-normal-incidence reflectivity, and by AFM surface observation.

Near-normal-incidence reflectivity of Mo/Al MLs in 41 layers was 33.5% at a wavelength of 18.5 nm at an incident angle of 10°, although the calculated reflectivity for an ideal structure was 59.6%. The decreasing reflectivity was mainly caused by the surface and interfacial roughness.

The surface roughness of Mo/Al MLs was dominated by the Al layer. We tried to improve the roughness of Al thin films. The roughness of Mo/Al ML decreased with decreasing RF power and increasing rotation speed of the substrate. High reflectivity is expected for Mo/Al MLs fabricated under the obtained conditions.

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