Fabrication of Mo/Si multilayer mirrors for extreme ultraviolet lithography by means of superconducting bulk magnet magnetron sputtering

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The fabrication of a highly reflective multi-layer film is an urgent need in the next-generation extreme ultraviolet (EUV) lithography to print ever-smaller circuit patterns onto semiconductor wafers by using extremely short wavelength (13.5 nm) light. For this purpose, we have synthesized the Mo/Si multi-layer films by employing the two-cathode superconducting bulk magnet magnetron sputtering apparatus. The films were made by repeatedly depositing a pair of 4.5 nm thick Si and then 2.5 nm thick Mo layer up to 40 or 50 pairs on the Si wafer with its root-mean square (rms) surface roughness of 0.1 nm. The resulting rms surface roughness of the Mo/Si multi-layer film turned out to be 0.12 nm. The transmission electron microscope (TEM) studies revealed the inter-diffusion layer thicknesses of Si-on-Mo and Mo-on-Si layers to be 0.5 and 1.5 nm, respectively. The EUV-reflectivity was theoretically calculated to reach the value of 70%, when these structural data are inserted into the reflectivity formula. However, the highest EUV-reflectivity so far observed was 67% in the normal incident condition. The 2–3% shortage of the reflectivity is attributed to the presence of residual Xe gas atoms incorporated into the film during deposition in the reduced Xe gas atmosphere.

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1. Introduction

A magnetized c-axis oriented single-domain bulk superconductor has been employed as a powerful permanent magnet for practical applications [1–4]. A superconducting magnetron sputtering apparatus was constructed by installing the magnetized bulk superconductor in place of the Nd–Fe–B permanent magnet [5–12]. It can capture much denser plasma over the target than a conventional magnetron sputtering as a result of the generation of an extremely strong magnetic field by the magnetized bulk superconductor. The degree of plasma confinement has been evaluated by using a parameter $B_{\text{max}}^l$, magnetic field being defined on the target as that directed parallel to its surface and, hence, possessing a vanishing vertical or z-component [5–12].

The $B_{\text{max}}^l$ value produced by the superconducting bulk magnet with 60 mm in diameter was reported to be 1.0 and 1.2 T on 3 and 1 mm thick Cu targets, respectively [7]. This is much higher than the value typical of only 0.05 T produced by the Nd–Fe–B magnet in a conventional magnetron sputtering. Such a large $B_{\text{max}}^l$ allowed us to deposit Cu in the Ar gas pressure range down to $3 \times 10^{-3}$ Pa in comparison with the working pressure range above $1.5 \times 10^{-1}$ Pa in a conventional one. Under such low inert gas pressures, the mean free path of sputtered atom reaches a few m. We could, therefore, deposit Cu onto the bottom of circular holes down to the diameter of 200 nm and the depth of 1.15 μm with its aspect ratio of about 6 in Si wafers [8].

Lithography is the technology used to print circuits onto computer chips. In order to pack more and more transistors onto a chip, semiconductor manufacturers must print ever-smaller features [13–15]. Extreme ultraviolet (EUV) lithography is a next-generation technology using the 13.5 nm wavelength. At such short wavelengths, one has to abandon ordinary optical lens and, instead, to use a multi-layer film like the stack of Mo/Si layers, which act to reflect light by means of interlayer interference. The reflectivity of the Mo/Si optical mirrors available now has reached the value of 65–67%. If reflectivity is increased say by 1% per mirror, a total increase in reflectivity is expected to reach 19% in a lithography system involving totally twelve mirrors. An increase in reflectivity by 1%, therefore, is of critical importance in shortening exposure time, which directly affects the enhancement in productivity.

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In the preceding works [10,11], we synthesized bi-layer films under different deposition conditions and reported the most appropriate deposition condition to minimize the thickness of the inter-diffusion layer formed in between Si and Mo layers. Both Ar and Xe were chosen as inert gas species. The gas pressure \( P \) varied over 0.005 up to 0.1 Pa while \( D_{st} \) over 100–600 mm and discharge voltage over 2–4 kV. It turned out that (1) Xe gas is better than Ar gas, (2) its pressure is around \( 4 \times 10^{-2} \) Pa, (3) a throw distance around 450 mm and (4) discharge voltage \( V \) around 2 kV [11].

The two-cathode superconducting magnetron sputtering apparatus is employed in the present work to fabricate Mo/Si multi-layer films with the aim at enhancing its EUV-reflectivity by making full use of the possession of a long mean free path of sputtered atoms so that plasma damage-free films are likely formed by increasing the distance between the target and substrate or throw distance \( D_{st} \) up to 600 mm [10–12].

2. Experimental

The structure of the present magnetron sputtering apparatus is already described elsewhere [10,11]. The generation of extremely strong magnetic field above the Mo and Si targets allowed us to discharge an inert gas in the pressure range down to \( \sim 4 \times 10^{-3} \) Pa. As a result, a throw distance \( D_{st} \) can be increased to the maximum of 600 mm. The DC electric voltage is supplied to the both targets up to 6 kV.

As mentioned in Section 1, we have optimized the deposition condition to minimize the inter-diffusion layer thickness between Si and Mo layers by using bi-layer films [11]. In the present work, we formed the Mo/Si multi-layer films on Si wafer substrate in the Xe gas atmosphere by depositing first 4.5 nm thick Si layer and then 2.5 nm thick Mo layer and by repeating the deposition of a pair of the resulting nominal 7 nm thick bi-layer film up to 40 or 50 pairs. The transmission electron microscope (TEM) was employed to study the cross-sectional structure of the 50-layer film. The rms (root-mean square) surface roughness was studied by using atomic force microscope (AFM). The EUV-reflectivity was measured for Mo/Si multi-layer films with the use of the CO2 gas-jet-target laser-plasma [11].

3. Results and discussion

Fig. 1 shows the cross-sectional image of TEM micrograph taken for the Mo/Si 50-layer film. A careful inspection of the photograph reveals the existence of two different inter-diffusion layers in multi-layer films: one formed upon deposition of Mo on the Si layer (hereafter referred to as Mo-on-Si) and the other that of Si on the Mo layer (Si-on-Mo). This is illustrated in Fig. 2. In it is found that the Mo-on-Si inter-diffusion layer thickness is 1.5 nm, which is three times as large as that of 0.5 nm for the Si-on-Mo. In the bi-layer experiments reported in [11], the deposition condition dependence of the inter-diffusion layer thickness was almost exclusively studied for films obtained by first depositing Si onto the Si wafer and then Mo layer. The resulting Mo-on-Si inter-diffusion layer was studied by means of the grazing incident X-ray reflectivity (GIXR). It is found that the Mo-on-Si effective inter-diffusion layer is more significantly reduced, when the Xe gas is used rather than Ar, and that the Mo-on-Si effective inter-diffusion layer thickness is minimized at \( V = 2 \) kV, \( P_{x} = 0.04 \) Pa and \( D_{st} = 450 \) mm [11]. However, the thickness of the Mo-on-Si effective inter-diffusion layer could not be lowered below 1.5 nm. Instead, we could recently confirm that the Si-on-Mo effective inter-diffusion layer thickness of the bi-layer film was as small as 0.5 nm from the GIXR measurements [12]. We consider it urgent to develop a technique to reduce the Mo-on-Si inter-diffusion layer thickness to the same level of 0.5 nm as that of the Si-on-Mo one.

Fig. 3a shows the AFM image of Si substrate just before the deposition of Mo/Si layers and b that of the surface of the 50-layer film. The rms surface roughness of Si substrate is 0.1 nm and is the best smooth surface available to us. The surface roughness after the 50-layer deposition increased its rms value only by 0.02 nm. The Xe gas pressure dependence of the rms surface roughness is plotted in Fig. 4 for the Mo/Si multi-layer films. There is a tendency for the rms surface roughness to decrease further with reducing Xe gas pressure and to approach nearly the value of the Si substrate. Thus, we can say that the superconducting magnetron sputtering is indeed advantageous over a conventional magnetron sputtering to produce a very smooth surface free from plasma-damage.

The EUV-reflectivity can be expressed as

\[
R = R_{0} \cdot \exp \left[ -\left( \frac{4\pi \sigma}{\lambda} \right)^{2} \right].
\]

where \( \sigma \) is the rms surface roughness of the multi-layer film and \( \lambda \) is the wavelength of the EUV-light equal to 13.5 nm [16,17]. The pre-exponential term \( R_{0} \) involves both the Si-on-Mo and Mo-on-Si inter-diffusion layer thicknesses as parameters. Fig. 5 shows the calculated EUV-reflectivity at the wave length of 13.5 nm as a function of the Mo-on-Si inter-diffusion layer thickness at three different values of rms surface roughness of 0.1, 0.2.
and 0.3 nm while fixing the Si-on-Mo inter-diffusion thickness to be 0.5 nm. We see from Fig. 5 that the EUV-reflectivity is increased about 2\%, if we can lower the rms surface roughness from 0.2 to 0.1 nm. This certainly emphasizes the importance in reducing the rms surface roughness as low as possible.

Fig. 6 shows the EUV-reflectivity data for the 50-layer film, for which the TEM and AFM measurements (see Figs. 1 and 3, respectively) were performed. The reflectivity of this sample in the normal incidence condition is found to be 67\% from the peak height. It is now interesting to examine how the EUV-reflectivity is affected by a structural quality of the multi-layer film. According to Eq. (1), the EUV-reflectivity is strongly dependent on the rms surface roughness and the thicknesses of the inter-diffusion layers Mo-on-Si and Si-on-Mo. The plot of the data in the form of Fig. 5 may be challenging, since all relevant data are available for the 50-layer film. The measured EUV-reflectivity is plotted in Fig. 7 as a function of the thickness of the Mo-on-Si inter-diffusion layer, while fixing the thickness of the Si-on-Mo inter-diffusion thickness to be 0.5 nm.

The data point marked with a double circle in Fig. 7 represents the measured EUV-reflectivity (Fig. 6) and the inter-diffusion layer thickness deduced from the TEM observation (Fig. 2). It is found to fall very near the calculated curve with the rms surface roughness and 0.3 nm while fixing the Si-on-Mo inter-diffusion thickness to be 0.5 nm. We see from Fig. 5 that the EUV-reflectivity is increased about 2\%, if we can lower the rms surface roughness from 0.2 to 0.1 nm. This certainly emphasizes the importance in reducing the rms surface roughness as low as possible.

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of 0.2 nm, in spite of the AFM observation demonstrating a much smoother value of 0.12 nm (see Fig. 3). We have synthesized several other multi-layer films under different deposition conditions and measured the EUV-reflectivity at 13.5 nm wavelength. Unfortunately, however, straightforward information about the Mo-on-Si and Si-on-Mo inter-diffusion thicknesses was not available, since TEM studies have not yet been performed for them. We may reasonably assume the Mo-on-Si inter-diffusion layer thickness to be uniquely determined under a given deposition condition, regardless of whether a bi- or multi-layer is grown. The value of the Mo-on-Si effective inter-diffusion layer thickness for the bi-layer films was determined from the GIXR measurement [11]. The EUV-reflectivity data coupled with the bi-layer structural data are incorporated in Fig. 7 with open circles. We see that measured reflectivity data fall between the curves with \( \sigma = 0.2 \) and 0.3 nm. As is found from Fig. 4, we consider it unlikely that the rms surface roughness is increased to 0.2–0.3 nm in these films. Instead, we believe the measured EUV-reflectivity to be affected by a factor, which is not explicitly taken into account in Eq. (1).

One possible factor is the existence of residual inert gas atoms inside the film. Using alpha-particles (He\(^{2+}\)) accelerated to 1.8 MeV, we measured the Rutherford backscattering (RBS) spectra for (a) sputtered Si and (b) sputtered Mo films and (c) the Mo/Si bi-layer film, all of which were deposited onto the Si wafer. As shown in Fig. 8a, we found a peak at about 1.6 MeV in the sputtered Si film. This was easily identified as the residual Xe gas incorporated during deposition in the Si gas atmosphere, since the peak is absent in the RBS spectrum of Si wafer itself. Though the Xe peak is hardly seen in the Mo film, as is shown in Fig. 8b, it seems premature to conclude that the Xe gas is exclusively liberated from the Si target. Then, its presence should be also detected in the Mo/Si multi-layer films. However it was apparently hidden under a rather broad tail of the Mo spectrum. Hence, we measured the RBS spectrum for the Mo/Si bi-layer film. As shown in Fig. 8c, the weak peak just above the Mo-edge was definitely observed. The amount of Xe gas atoms in the bi-layer film was roughly estimated to be approximately 0.02\% from the peak height. The absorption coefficient due to Xe atom at the wave length of 13.5 nm is fairly large and is about ten times as large as that due to Mo atom [18]. Hence, we consider the EUV-light to be likely absorbed by Xe atoms through their ionization by emitting photoelectrons or secondary electrons. This is, we believe, responsible for lowering the EUV-reflectivity by 2 to 3% relative to that expected only from the structure data. Further work along this line is under progress.

4. Conclusions

We have synthesized the Mo/Si multi-layer films by using the two-cathode magnetron sputtering apparatus equipped with superconducting permanent magnet we developed and analyzed the structure and its effect on the EUV-reflectivity. The highest
reflectivity so far obtained is 67% in the normal incidence condition. By using the superconducting magnetron sputtering, we could produce a very smooth top surface of the Mo/Si multi-layer films free from plasma-damage. The 2–3% shortage of the EUV-reflectivity from that calculated from the structure data is attributed to the presence of residual Xe gas atoms incorporated into the film during the deposition under the Xe gas atmosphere.

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