

Pattern Formation of Sputtered Films by Deposition through Mask

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The thickness of the film near the edge of a film pattern formed by sputter deposition through a mask is not uniform, because of the shadowing effect of the side wall of the mask edge. When the effect is large, a sharp pattern can not be obtained. In order to clarify the precision or the sharpness of the film pattern, the distribution of the film thickness near the pattern edge was measured. It was found that the sharpness depended on the position of the pattern edge and the attitude of the side wall of the mask. A mask with bridges was contrived for the formation of an isolated space in a film, and the film deposition under the bridge was observed. It was found that the ratio of the gap between the substrate and the bridge to the bridge width must be larger than 1.0 for the thickness under the bridge to be greater than half the full thickness.

KEYWORDS: sputtering, mask, thin film, pattern formation, thickness distribution, silver film

1. Introduction

There are two methods for pattern formation of thin films. One is to etch a film after deposition and the other is to deposit a film through a mask which is usually made of a metal such as stainless steel. The latter has some advantages. It is economical because it is simple and requires no complicated processes after deposition. However, it is usually only applicable to the formation of patterns with a scale larger than 0.1 mm, while the former can be applied to much finer patterns. This is because the edge of the pattern of the film lacks sharpness and also because it is difficult to obtain a mask with a fine pattern. One of the causes of the lack of pattern sharpness is the thickness of the mask material. The film deposited at a position shaded by the mask edge is thinner than that at a position which is not shaded. Furthermore, when a gap is formed between the substrate and the mask because of mask bending due to, e.g., heat stress in the mask material during the sputter deposition, the lack of sharpness becomes more serious. This effect is especially significant when the mask is made of a metal plate larger than 100 mm and the mask is, as it usually is, fixed to the substrate holder at the edges. In this case, the total expansion between the fixed points is large and the mask bending brought about for the absorption of the expansion is severe. In order to form a fine pattern precisely by deposition through a mask, it is important to clarify the pattern sharpness, i.e., the distribution of the film thickness near a pattern edge. Thus, we deposited Ag films through masks and measured the thickness distributions near the pattern edges. The results were compared with calculated thickness distributions. Another purpose of this study is to consider a method to form an isolated space in a film by deposition through a mask. As shown later, this can be achieved by using a mask which has bridges. To discuss the design of the mask with bridges, the distribution of the thickness of the film deposited under bridges was measured and analyzed in comparison with the calculated results.

2. Experimental

2.1 Measurement of film thickness near pattern edge

The sputtering apparatus used in the experiment was a dc magnetron type. Its detailed structure has been illustrated previously.¹⁾ The diameter of the cathode (Ag target) and that of the anode were both 100 mm and the distance between the target and the substrate was 30 mm. In Fig. 1, the film deposition around a mask edge is illustrated. Using a glass plate with a size of 10 × 10 × 0.41 mm as a mask, we deposited films on glass substrates and measured the thickness distribution near the pattern edge using a surface roughness tester. Here, it must be noted that half the glass mask covered a glass spacer with a thickness equal to the gap length. The mask was fixed only at the part covering the spacer and the part overhanging from the spacer edge was free. Furthermore, the thermal expansion coefficient of glass is much smaller than that of stainless steel. Therefore, it was considered that the mask did not bend during deposition. In the investigation, the gap length G between the substrate and the glass mask, the position of the mask edge R and

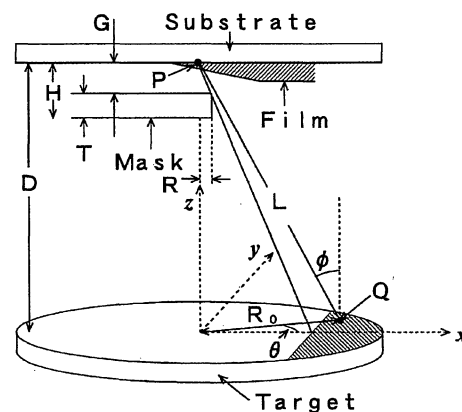


Fig. 1. Illustration of film deposition through a mask. The atoms deposited at the point P come from the shaded area on the target.

the Ar gas pressure were changed. The discharge voltage was fixed at 500 V. The Ar gas pressure was 0.09–2.7 Pa. The electric current was 40–150 mA and the deposition rate was 0.8–2.4 nm/s depending on the Ar gas pressure.

2.2 Measurement of film thickness under bridge

An example of a mask which has bridges is illustrated in Fig. 2(a). It is easily inferred that an isolated space can be made in a film using this mask. The film deposition under a bridge is illustrated in Fig. 2(b). The thickness of the film under a bridge should increase with decreasing bridge width W or with increasing gap G between the bridge and the substrate. Regarding strips of ceramic or stainless steel as bridges, we deposited films on glass substrates. Here, it must be noted again that only one side of a strip was fixed on one spacer and the other side was placed free on the other spacer, and that the strip was short (about 10 mm). Thus, bending of the strips was considered to be negligible. The thickness of the strips T and the gap G were fixed at 0.1 mm and 0.2 mm, respectively, and the width W was between 0.15 and 0.5 mm.

2.3 Measurement of erosion depth of target

The sputtering target was coated with carbon powder paste over a width of a few mm along its diameter. After film deposition, the carbon paste was removed and the height of the step formed between the area where the paste had been coated and that where the paste had not been coated was measured using a surface roughness tester. The step height was measured at intervals of a few mm. In Fig. 3, the erosion depth distribution thus obtained for Ar gas pressure of 0.27 Pa is shown along the target diameter. It shows that the target is most deeply eroded at about 30 mm from the target center. The distribution depended little on the Ar gas pressure.

3. Calculation

There are two simulation methods for analysis of the thickness of sputtered films. One is equivalent to that used for the calculation of illuminance^{1–7)} and the other

is the Monte Carlo method which takes account of the effect of scattering by the discharge gas.^{8–14)} The latter was first considered by Motohiro and Taga for analysis of the thermalization of the sputtered atoms and the film deposition on the front and back surfaces of the substrate.^{9–11)} Recently, it has been improved for more accurate treatment of the interatomic potential.¹⁴⁾ Although the former is not appropriate when the gas pressure is high, it has been successfully applied to deposition at low pressure, as in the case of magnetron sputtering. For instance, distributions of the film thickness with regard to various geometries of the sputtering apparatus and various target structures, were calculated.^{1–5)} The shadowing effect observed in the step coverage was calculated by Blech⁶⁾ and Neureuter.⁷⁾ Those studies showed that the calculation by the former method, on the whole, gave satisfactory results. Considering that the scattering angle of sputtered Ag atoms is not large because their weight is greater than that of Ar atoms, it is expected that the former method would be appropriate at least for deposition at a low pressure. Therefore, the former method was adopted in this study.

Figure 1 illustrates the method for the calculation of the film thickness around a mask edge. It is assumed that the sputtered atoms proceed directly without scattering by Ar gas and that the angular distribution of sputtered atoms follows a cosine distribution. Then, the film thickness at a point P on the substrate is given by²⁾

$$t = \iint \frac{\cos^2 \phi}{\pi L^2} E R_0 dR_0 d\theta. \quad (1)$$

Here, L is the distance between the deposition point P and the ejection point Q. R_0 and θ define the point Q. The angle ϕ specifies the direction of ejection of sputtered atoms. The erosion depth E as a function of R_0 is already shown in Fig. 3. When P is on the inner part of the eaves of the mask, as shown in Fig. 1, the area over which integration (1) is performed is

$$\begin{aligned} R_0 \cdot \cos \theta &> R - \frac{X \cdot (D - G)}{G}, \\ &\equiv R - X \cdot \frac{D}{G}, \end{aligned} \quad (2)$$

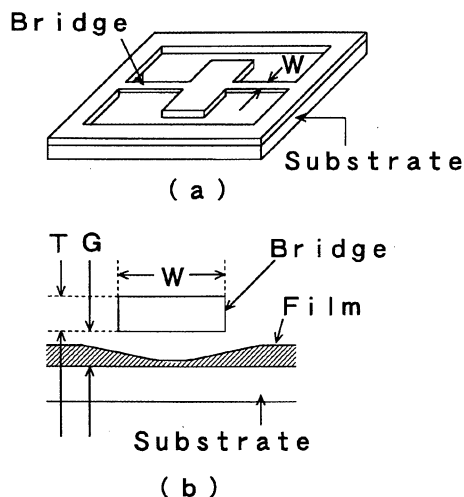


Fig. 2. A mask which has bridges (a) and film deposition under a bridge (b).

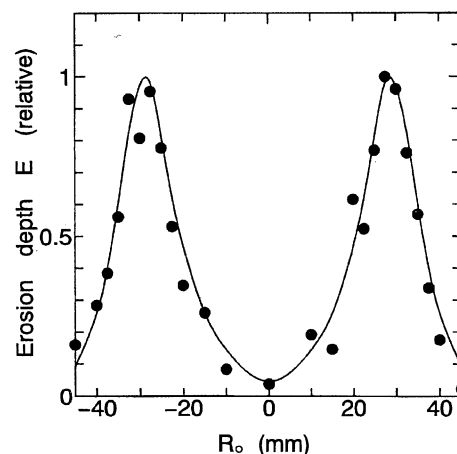


Fig. 3. Distribution of the erosion depth of an Ag target as a function of the distance R_0 from the target center. The target is most deeply eroded at the position about 30 mm from the center.

where R is the distance between the anode center and the mask edge and $-X$ (X is negative in the case of Fig. 1) is the distance between the mask edge and P. The gap G is assumed to be negligible compared with D , the distance between the target and the substrate. The area specified by inequality (2) is shown as the shaded area in Fig. 1. When P is on the outer part of the eaves ($X > 0$), the area of integration is

$$R_0 \cdot \cos \theta > R - \frac{X \cdot (D - H)}{H},$$

$$\Rightarrow R - X \cdot \frac{D}{H}, \quad (3)$$

where H , the distance between the mask surface and that of the substrate, is the sum of the mask thickness T and the gap G and is assumed to be far smaller than D . The integration was carried out as a summation of the integrand, where the numerical values of R_0 and θ were given at 1 mm intervals and at 1° intervals, respectively. The film thickness under a bridge was calculated in the same manner.

4. Results and Discussion

4.1 Film deposition around mask edge

First, the distribution of the full thickness, the thickness at positions not undergoing shadowing effect, measured along the diameter of the anode plate is plotted by solid circles in Fig. 4, as a function of the distance from the anode center. The Ar gas pressure is 0.27 Pa. The distribution is normalized so that the thickness at the anode center is 1. The calculated distribution is also shown in the figure by a solid curve which almost agrees with the measured data.

As shown in Fig. 4, the area in which good uniformity of the film thickness is maintained is within 30 mm of the anode center. Therefore, the measurement of the pattern sharpness was carried out in that area. Figure 5 shows the distribution of the thickness relative to the full thickness, as a function of the distance from the mask edge X . The data are for three positions of the mask edge, i.e., the center position ($R = 0$ mm) and positions away from the center ($R = 30$ or -30 mm). The Ar gas pres-

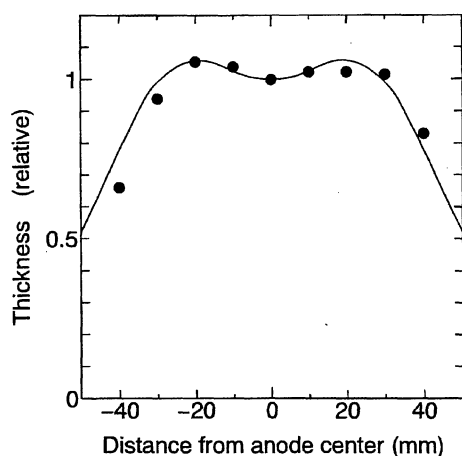


Fig. 4. Film thickness as a function of the distance from the anode center. The experimental data are plotted as solid circles and the calculated data is shown by a solid curve.

sure is 0.27 Pa and the mask thickness is 0.41 mm. The calculated distributions indicated by solid curves nearly agree with the measured ones regardless of the position of the mask edge. The mean free path of Ag atoms under the pressure of 0.27 Pa is 114 mm, considering the Ar gas temperature measured by a thermocouple to be about 480 K and assuming the atomic radius of Ag atoms and that of Ar atoms to be 0.24 nm and 0.26 nm, respectively.¹⁰⁾ Because this length is larger than the distance of 30 mm between the target and the substrate, the assumption in the calculation that the sputtered atoms do not undergo scattering by Ar gas is valid. For the center position, the thickness is 0 for negative values of X and increases with increasing X . As X approaches the value of the mask thickness, 0.41 mm, the film thickness approaches 1.0. Thus, the unsharpness of the pattern, i.e., the width over which the film thickness abruptly changes along the normal to the edge of the film pattern is roughly the mask thickness, at least at the center position. However, at $R = 30$ mm, where the side wall of the mask edge faces outwards, the approach to 1.0 is slower and the pattern is less sharp. This is because the shadowing effect is larger at that position. Contrary to this, the approach to 1.0 is faster at $R = -30$ mm. The effect of the Ar gas pressure was observed. Figure 6 shows that the distribution for the lowest pressure (0.09 Pa) and that for the highest pressure (2.7 Pa) are not greatly different. The data calculated using eq. (1), shown by the solid curve, agrees reasonably well with the measured data. The incidence of atoms on a substrate at high pressure is considered to be isotropic as pointed out by Nanbu and Honda.¹²⁾ Thus, the distribution was also calculated on the assumption of isotropic incidence. The data is shown by the dotted curve in the figure. The two calculated data are not much different. These results suggest that the incidence is roughly isotropic even for low pressure, at least in the area sufficiently inside the erosion ring. In other words, as long as the mask edge is positioned inside the erosion ring, the effect of scattering is not so apparent even at a high pressure.

One of the reasons why the present study was carried

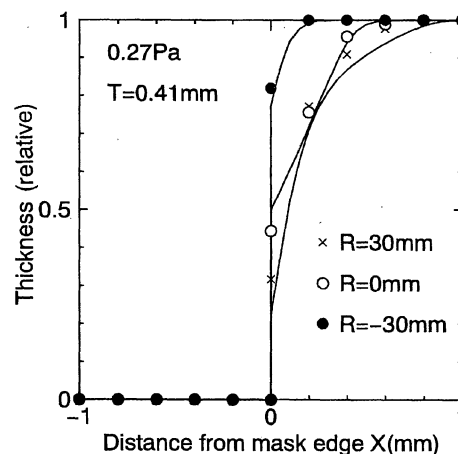


Fig. 5. Thickness distributions near pattern edges as functions of X , the distance from the mask edge. They are normalized so that the full thickness is one. Data for three positions, $R = 0$, 30 and -30 mm, are shown.

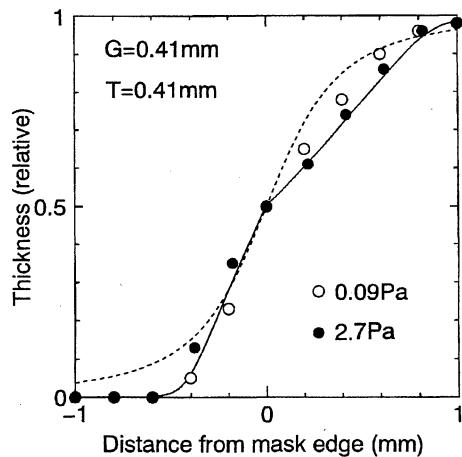


Fig. 6. Influence of the Ar gas pressure on the thickness distribution near the pattern edge. The solid curve is calculated using eq. (1) and the dotted curve is calculated by assuming isotropic incidence.

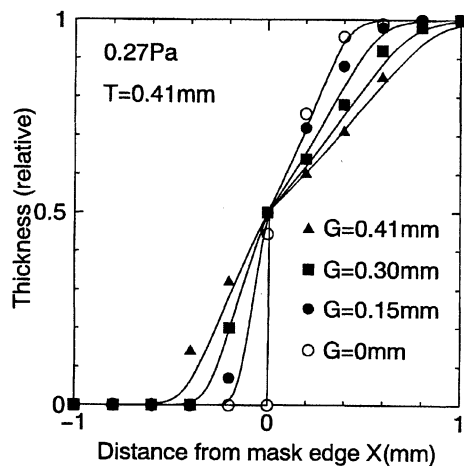


Fig. 7. Thickness distributions around the edges of masks which have a gap. The pattern becomes less sharp as the gap becomes larger. The calculated results shown by solid curves reproduce the measured data well.

out was that we previously observed that the patterns of film electrodes used in electric devices occasionally become dull due to the gap formed between the substrate and the mask. During the sputter deposition, the temperature of the mask easily exceeds one hundred °C. This causes expansion of the mask material which is usually stainless steel. Thus, when the mask size is large and the mask is fixed at several points, a gap as large as a few mm is produced and the electrodes which should be isolated from each other are shorted. Figure 7 shows the thickness distribution near the edge of a mask which has a gap. The film turns around behind the mask by the depth nearly equal to the gap length and the pattern becomes less sharp as the gap becomes larger. The calculated results again reproduce the measured data well.

It may be useful to give the thickness distributions around mask edges in terms of a more universal expression. The distribution of the film thickness near a mask edge depends on the gap G and the mask height H ($= T + G$). However, by reducing them as functions of X/H or X/G , they can be shown more generally. Figure 8 shows the reduced thickness distributions obtained by calculation as well as from the experimental data given in Fig. 7. From this figure, it is possible to obtain the film thickness on the inside of the mask as a function of X/G and the film thickness on the outside of the eaves as a function of X/H .

4.2 Film deposition under bridge

In order to make an isolated space in a film, we considered a mask which has bridges, as shown in Fig. 2(a). This mask can be made by thinning the bridge using etching technique. When an isolated film is deposited using this mask, the film under the bridge should have sufficient thickness. The thickness distribution under a strip of ceramic or stainless steel bridge is shown in Fig. 9. The gap length and the thickness of the bridge are 0.2 mm and 0.1 mm, respectively. The figure shows that the film under the bridge becomes thinner with increasing bridge width. An interesting phenomenon that the distribution for the bridge 0.15 mm wide has a small

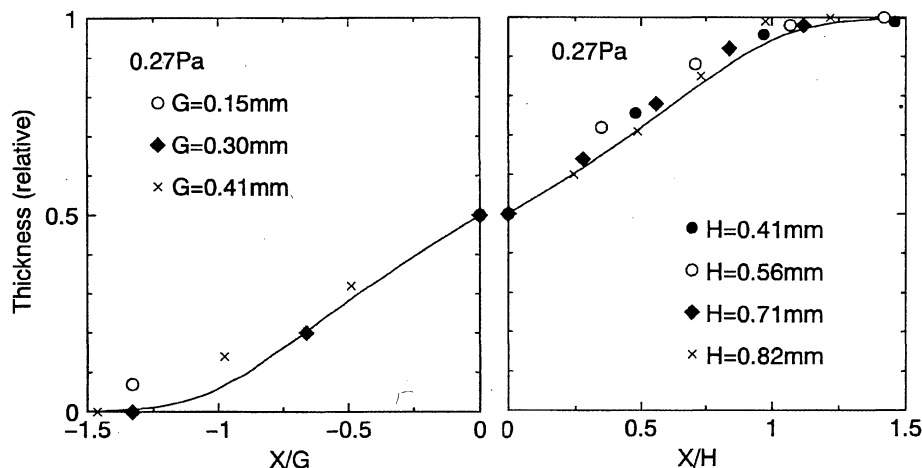


Fig. 8. Reduced thickness distribution near a pattern edge. The thickness inside and that outside the mask eaves are reduced as a function of X/G and a function of X/H , respectively. The measured data are plotted in addition to the calculated curve.

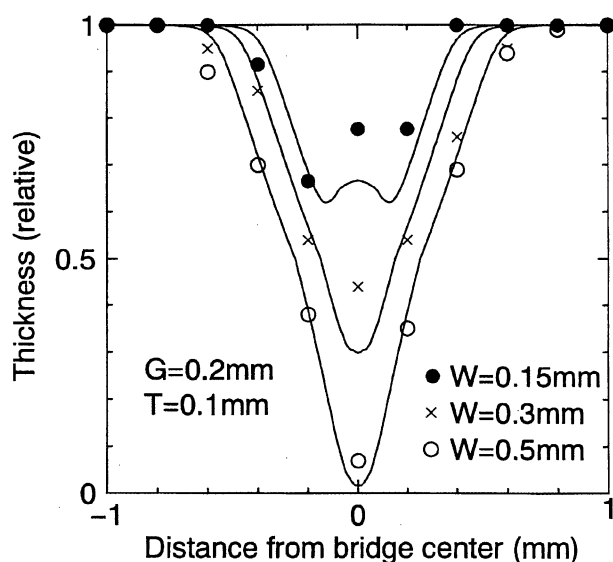


Fig. 9. Thickness distribution under a bridge. The calculated data shown by the solid curves nearly agree with the measured data.

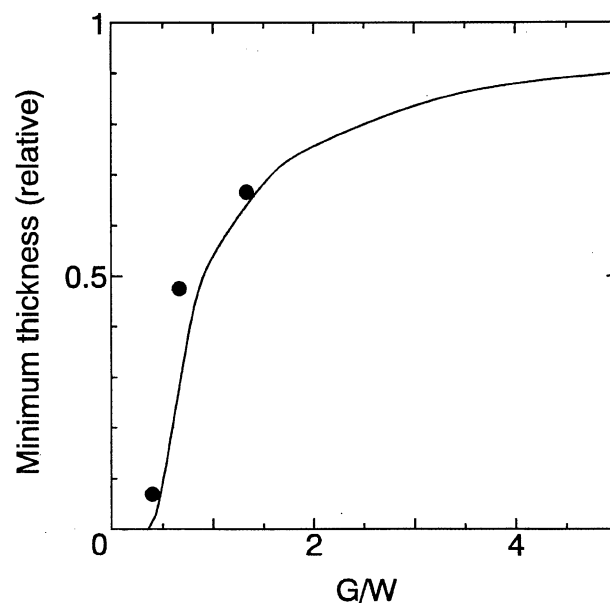


Fig. 10. Minimum thickness under a bridge reduced as a function of G/W . Three experimental values obtained from Fig. 9 are plotted as well as the calculated curve.

peak at the center of the bridge width is seen. The calculated data in the figure nearly reproduce the measured data, including such detailed behavior. This peak reflects the localized target erosion represented in Fig. 3, since the distribution calculated for uniform target erosion does not show a peak. When a mask with bridges is designed, the width W and the gap G of the bridge must be determined so that the film under bridge is sufficiently thick. Figure 10 shows the minimum thickness under a bridge obtained by calculation as a function of the W/G ratio. The three experimental data obtained from Fig. 9 are also plotted in the figure and are found to be close to the calculated curve. From the figure, one can obtain the W/G ratio necessary for making the film under a bridge thicker than the prescribed value. For instance, in order to obtain a thickness larger than half the full thickness, the W/G ratio must be larger than about 1.0.

5. Conclusions

To discuss the sharpness of the film pattern formed by sputter deposition through a mask, the thickness distribution of a film near a pattern edge was measured. A mask with bridges was considered for the formation of an isolated space in a film, and the film thickness under the bridge was measured. The results are summarized as follows.

(1) The unsharpness of the film pattern, i.e., the width over which the film thickness abruptly changes along the normal to the edge of the film pattern is nearly equal to the thickness of the mask material, at least near the anode center.

(2) The unsharpness is larger when the mask edge is away from the center and the side wall of the mask faces the outside of the sputter system, while it is smaller when the side wall faces inwards.

(3) When a gap exists between the mask and the substrate, the width of the unsharpness increases by the length nearly equal to the gap.

(4) The thickness under a bridge is given as a function of the gap to width ratio G/W .

(5) The thickness near a mask edge and that under a bridge can be calculated with considerable accuracy using the model presented here.

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