Effect of an electric field on the growth of aluminum film

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An electric field is applied to the substrate during the growth of aluminum films, with the results that the reflectance is increased, scattering is reduced, and the surface is smoothed.

Key words: Electric field, aluminum film, reflectance, scattering, surface roughness.

1. Introduction

Al coatings are widely used as high reflectors for many applications. Al films are usually deposited on glass substrates by thermal evaporation through the use of resistively heated tungsten coils.

Owing to the low kinetic energy of evaporants, thermal evaporated films are less dense than their bulk material, with the result that the film surface cannot be very smooth.[1–2]

In order to increase the mobility of the evaporants, several methods have been used, such as plasma sputtering[3–6] (dc or rf magnetron), ion plating,[7–9] ion-beam sputtering,[10–13] and ion-assisted deposition,[14–18] or simply heating up the substrate temperature.

Alternatively, bias voltage has been applied and has shown influences on the film properties.[19–23]

Here we show the method and the results of applying a longitudinal electric field in front of the substrate during deposition. Lower scattering of Al thin films and higher reflectance can be obtained for the Al films deposited by this method.

2. Experimental Procedures

All Al films were deposited by resistively heated tungsten coils at room temperature with a base pressure of 8×10^{-6} Torr. The purity of the source Al was 99.999%. A 1-in.-(2.54-cm-) diameter BK-7 substrate was set ~ 30 cm directly above the vapor source. A longitudinal electric field was applied to the substrate by setting an electrode annulus in front of the substrate. The distance between electrode and substrate was 5 mm. High voltages up to 2.4 kV had been applied to the electrode during the growing of Al films. A thermal-electron emitter was set beside the vapor source. The schematic drawing of the deposition setup is shown in Fig. 1. The evaporation rate is 30 Å/s, and the final thickness of the film is 1200 Å, as measured by a quartz monitor.

Reflectance of the deposited Al films were measured with a spectrophotometer (Hitachi U3501). An integrating sphere was used for measuring the surface scattering of the deposited films. Figure 2 shows the integrating sphere setup for the measurement of the scatterings. The surface roughness of the Al films were measured with a Sloan DEKTAK Profiler.

3. Results and Discussions

Reflectances of the Al films deposited with and without an applied electric field were measured with a Hitachi U3501 spectrophotometer at a 5° angle of incidence. The increasing reflectance difference $\Delta R\%$ is shown in Fig. 3 as a function of the applied voltages, where $\Delta R = R_v - R$, and R_v and R are the reflectances of Al films deposited with and without applied voltages, respectively. The percentage of ΔR with voltages less than 400 V was not obvious and is not shown in the figure.

The surface scatterings measured by the integrating sphere (Fig. 2) decreased as the applied voltages increased. Figure 4 shows such a decrease as a function of the applied voltages, where $\Delta S = S_v - S$, and S_v and S are surface scatterings of the Al films deposited with and without applied voltages, respectively.

In order to confirm that an increase in reflectance

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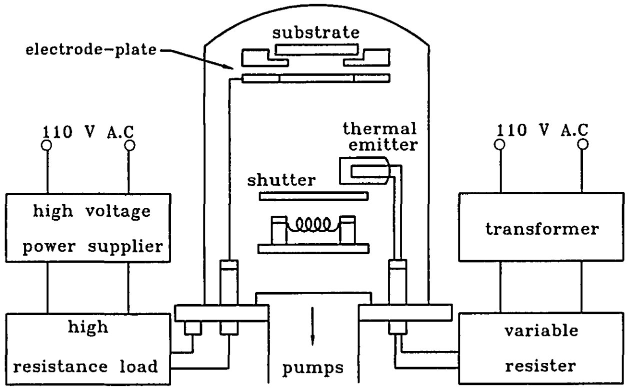

Fig. 1. Setup of the deposition system.

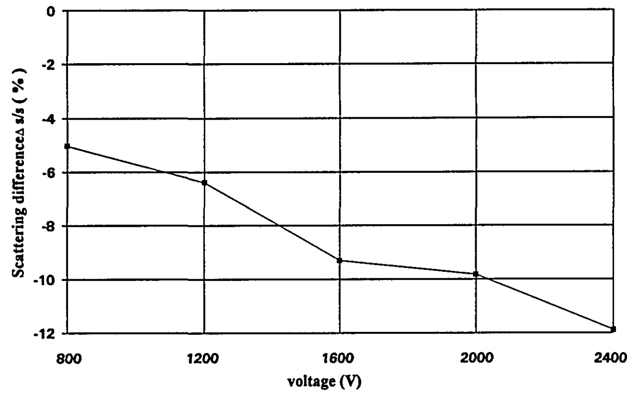

Fig. 4. Scattering difference $\Delta S/S$ versus applied voltage.

and a decrease in scattering are due to the smoothing in the Al film surface, we measured the surface roughness of the Al films. Figure 5 shows the surface roughness of the Al films measured with a Sloan DEKTAK profiler. It is easy to see the influence of the electric field on the improvement of the surface roughness from that figure. We plotted the root-mean-square σ (rms) of the Al film surface roughnesses versus the applied voltages in Fig. 6. The rms σ is monotonically decreased in the same way as scatterings are when applied voltages are increased. Table 1 lists the rms σ of Al films for different applied voltages of three depositions. The last column in Table 1 gives the averages of the three measurements.

Table 2 lists the total integrated scattering reduction for different wavelengths with different applied voltages; there is a higher scattering reduction with applied voltages for shorter wavelengths than that for

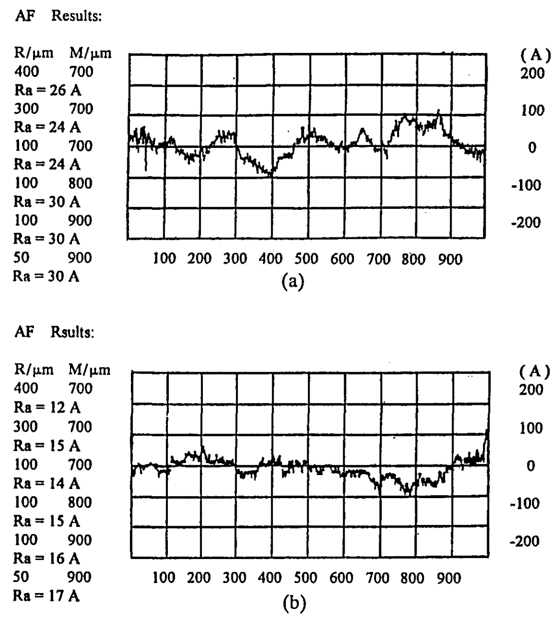

Fig. 5. Surface roughness measured with a step styler. (a) Applied voltage 1200 V, (b) applied voltage 2400 V.

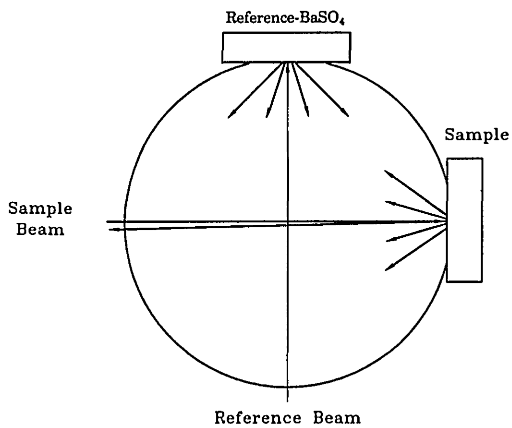

Fig. 2. Measurement of scattering with an integrating sphere.

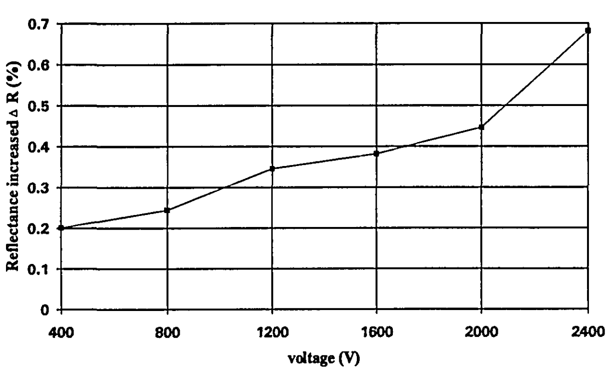

Fig. 3. Increase in reflectance ΔR versus applied voltage.

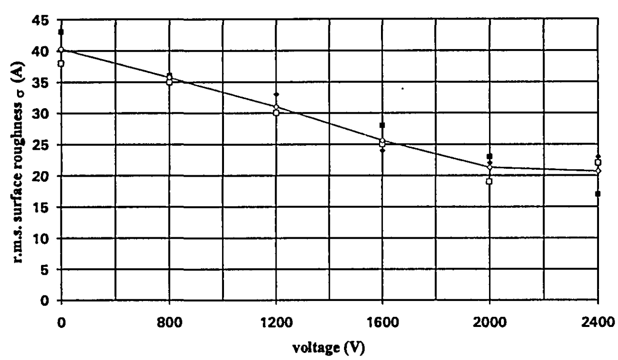

Fig. 6. rms surface roughness σ versus applied voltage.

Table 1. rms Surface Roughness versus Applied Voltage

Number	Voltage (V)	σ_1 (A)	σ_2 (A)	σ_3 (A)	σ (average)
1	0	43	38	40	40.3
2	800	36	35	36	35.7
3	1200	30	30	33	31
4	1600	28	25	24	25.6
5	2000	23	19	22	21.3
6	2400	17	22	23	20.7

a longer wavelength. For the spherical scatterer with dimensions much smaller than the wavelength, the scatter intensity has an inverse fourth-power dependence on wavelength in all directions.[24] For the scatterer with dimensions much greater than the wavelength, the scatter intensity has an inverse second-power dependence on wavelength in the forward direction.[25] If we assume that it is generally true that the power in the inverse power-law dependence on wavelength for scatter intensity decreases as the scatterer dimension increases, then Table 2 implies qualitatively that the effect of applying voltage is to increase the scatterer dimension on the film surface. Table 2 also implies that increasing the applied voltage leads to an increase in the scatterer dimension, and we believe that it is possible that the increase in the dimension of the columnar structure of the Al film leads to this phenomenon. A consequence of increasing columnar dimension is a smoother surface, which is supported by our surface roughness measurement, as mentioned above. Further systematic investigation by scanning electron microscopy on the morphology of the films will be very helpful in answering these questions.

We believe that the increase of the columnar dimension and hence the decrease of the surface roughness by the applied electric field is due to the increase of the surface mobility, i.e., mobility parallel to the surface of the film, of the impinging Al atoms. The cause for the increasing surface mobility could be electronic or ionic, as discussed below. The impinging Al atom could gain extra surface mobility by colliding with the electrons that are thermionically emitted from the tungsten coil and source Al; the electrons were accelerated by the applied electric field to gain sufficient energy. It is also possible that some Al atoms were negatively charged and were accelerated by the applied field to gain sufficient energy to increase the surface mobility. The negatively charged Al atom could be formed from the neutral evaporated Al atom charged by the electrons that were emitted from the thermal emitter located beside the evaporation source. One observation we have made was that shutting off the thermal emitter has little influence on our results. This observation implied that the phenomenon is electronic rather than ionic dominated. One could arrange further investigation of this assertion by applying a magnetic field close to the evaporation source, such that the light electron deviates more from the path than the heavy ion, and only the negatively charged Al ion could be accelerated by the applied electric field. In our experiment, only a longitudinal electric field was applied. It would be interesting to see whether a transverse electric field or a transverse magnetic field applied close to the substrate would enhance the effect, since a transverse electric field or a transverse magnetic field would increase the momentum of the charged particle in the direction parallel to the film surface, and therefore further increase the surface mobility of the impinging Al atoms.

Table 2. Scattering Reduced at Different Wavelengths versus Applied Voltage

Number	Voltage (V)	Wavelength (nm) 400	500	600	700
1	800	−1.79	−1.51	−1.15	−1
2	1200	−1.77	−1.73	−1.71	−1.66
3	1600	−2.54	−2.51	−2.48	−2.46
4	2000	−2.59	−2.63	−2.62	−2.61
5	2400	−3.29	−3.22	−3.17	−3.12

4. Conclusions

A longitudinal electric field applied to the substrate has proved to be influential in the growth of Al films. The reflectance of the film was increased and the surface scattering of the film was decreased as the applied voltage was increased.

The increase of reflectance and the decrease of scattering are due to an increase in the mobility of the condensing Al atoms. The film surface roughness is thus reduced. These effects are more pronounced for a shorter wavelength than for a longer wavelength.

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