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The mechanism of an increase in electrical resistance in Al thin film induced by current stressing

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ABSTRACT

A 10 mm × 2 mm × 500 nm Al thin film was stressed with electric current at 1.5–3.0 × 10^5 A cm^{-2} for 1 h under an ambient atmosphere. *Ex situ* variations in the sheet resistance induced by current stressing were measured with a four-point probe. The critical current density for the resistance change was observed between 1.5 × 10^5 and 2.0 × 10^5 A cm^{-2}. The electrical resistance reached a maximum increment of 5.47% at 2.5 × 10^5 A cm^{-2}. The lattice structure of the Al thin film was investigated with a high resolution transmission electron microscope to determine the fundamental effects of electric current stressing on the electrical property of the metal film. The high resolution lattice images incorporating a selected area fast Fourier transform indicated a large degree of lattice distortion and high dislocation density, up to 8.60 × 10^{16} m^{-2}, in the metal film after current stressing at 3.0 × 10^5 A cm^{-2}. The dislocations are believed to have been generated by the impingement of electron wind. *In situ* synchrotron X-ray diffraction further evidenced a high degree of lattice strain, as great as 1.1% at 3.0 × 10^5 A cm^{-2}, as estimated from the low angle shifts in the diffraction peaks. The generation of dislocations and the lattice strain induced by current stressing were orientation-dependent, as determined by the d-spacing of the lattice orientation. The formation of a high dislocation density and the subsequent buildup of lattice strain caused to an increase in electrical resistance of the Al thin film.

1. Introduction

Electromigration in Al thin film has been shown to induce an abrupt increase in electrical resistance and to result in open circuit failure at the later stage of current stressing [1]. An *in situ* scanning electron microscope observation evidenced the nucleation and growth of voids during current stressing [2]. These voids have further been shown to build up the tensile stress at the cathode and the stress gradient in the metal film, as revealed by an *in situ* transmission X-ray topography [3]. The abrupt increase in electrical resistance at the later stage of current stressing is generally believed to be mainly due to the accumulation of the voids observed at the cathode.

It has also been shown that there is an increase in electrical resistance of Al thin film at the early stage of current stressing, which occurs long before the formation of observable voids [4–6]. This early increase in electrical resistance has been ascribed to the generation of excess vacancies induced by the divergence of electromigration flux [4,5]. It has also been inferred that the buildup of stress in metal film that exceeds the yield stress and induces plastic deformation can attribute to an early increase in electrical resistance [6]. The plastic deformation behavior of Al thin film, such as grain rotation, grain bending, and subgrain formation, have been investigated at the early stage of current stressing in view of the generation and motion of dislocations, as observed using synchrotron Laue X-ray microdiffraction [7,8]. It can be concluded accordingly from the above mentioned studies that the generation of vacancies and dislocations in Al thin film at the early stage of current stressing builds up the stress beyond the yielding stress and induces plastic deformation. This may further cause an increase in electrical resistance. However, no study has reported direct observation of excess vacancies or dislocations in the lattice structure of Al thin film. There is little understanding of variations in the lattice structure of metal film induced by current stressing.

We recently investigated the existence of dislocations in current stressed solders using a high resolution transmission electron microscope (HRTEM) [9,10]. In the present study, the fundamental effects of electric current stressing on the electrical property of Al thin film were investigated. The increase in electrical resistance observed in the present study was correlated with the formation of a high dislocation density and the subsequent buildup of lattice strain in the metal film.

2. Experimental details

A 10 mm × 2 mm × 500 nm sputtering deposited Al thin film was applied for the current stressing study, as shown in Fig. 1. The specimen was annealed at 380 °C (0.7 T_m) for 6 h in a N_2 atmosphere prior to

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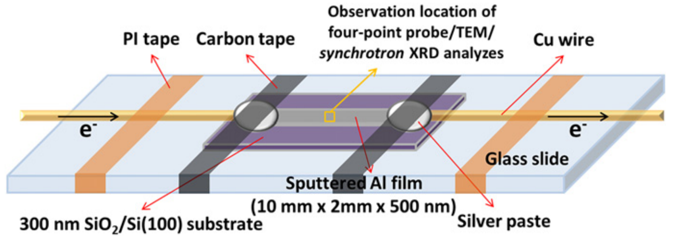

Fig. 1. Schematic diagram of the sputtering deposited Al thin film stressed with electric current.

electric current stressing to reduce the intrinsic defects. The as-annealed Al thin films were stressed with electric current at 1.5, 2.0, 2.5, and 3 × 10^5 A cm^{-2} for 1 h under an ambient atmosphere. During electric current stressing, the steady-state temperatures at various current densities were measured with a K-type thermocouple. The thermocouple was attached to the middle of the metal film for the measurement. The specimens were subsequently subjected to electrical and microstructural analyses. The electrical resistances of the metal films were measured *ex situ* with a four-point probe at room temperature after the dissipation of the Joule heat to avoid temperature effects. The probes were indented in the middle of the metal film for the measurement, as shown in Fig. 1. The distance between the neighboring probes was 1 mm. The electrical resistance for each of the testing conditions was averaged over three specimens. The standard deviation was also presented for the purpose of clarifying the interpretation of the data. TEM specimens were made from the middle of the Al thin film. The grain size of the Al thin film was averaged over six grains on the HRTEM image. The lattice structure and the estimation of dislocation density were further investigated with a selected area fast Fourier transform (FFT) diffraction pattern incorporated with the inverse fast Fourier transform (IFFT) treatment. The dislocation density for each of the testing conditions was statistically estimated at the same location (in the middle of the Al thin film) under an ambient condition in terms of the number of Burgers vectors per unit area. Three individual 13.5 nm × 13.5 nm regions within the same Al grain were chosen from near the grain boundary to the middle of the given Al grain to evaluate the average dislocation density. The obtained value thereby represented the average dislocation density in the same Al grain with respect to various locations. *In situ* variations in the lattice strains induced by current stressing were estimated from the peak shifts using synchrotron X-ray diffraction (XRD) during current stressing for 1 h. The XRD scanning was conducted in the middle of the Al thin film. The peak scanning continued for an additional 40 min following stoppage of the electric current stressing to investigate the recovery behavior of the peak. In a separate experiment, the Al thin films were heated to the specific temperatures corresponding to those for the current stressed specimens at various current densities. The temperature was measured with the thermocouple built in the XRD sample stage. The heated Al thin films were analyzed with a synchrotron XRD to obtain the benchmark thermal strains for comparison.

3. Results and discussion

3.1. Variations in the electrical resistance of the Al thin film induced by current stressing

The sheet resistance of the annealed Al thin film was 0.116 ± 0.002 Ω sq^{-1}. Fig. 2 presents *ex situ* variations (%) in the sheet resistance of the Al thin film induced by current stressing at 1.5–3.0 × 10^5 A cm^{-2} for 1 h. The electrical resistance was nearly unchanged, a variation of −0.47%, at a current density of 1.5 × 10^5 A cm^{-2}. When the metal film was stressed with a higher current density of 2.0 × 10^5 A cm^{-2} or above, the electrical resistance increased with respect to various current densities and reached a maximum increment of 5.47% at 2.5 × 10^5 A cm^{-2}. The critical current density for the increase in electrical resistance was thus between 1.5 × 10^5 and 2.0 × 10^5 A cm^{-2}. The existence of a critical density for changes in electrical resistance has been reported in the literature. The critical current density has been shown to be governed by the length of the specimen [6]. Fig. 2 further indicates that the degree of the increase in electrical resistance was reduced to 1.70% at a higher current density of 3.0 × 10^5 A cm^{-2}. The results obtained herein reflect the average electrical resistances in the middle of the metal film regardless of the polarization effect. It has been reported that electric current stressing of pure Sn induces a 10% decrease in electrical resistance as a result of grain rotation [11]. Pure grain rotation with no grain growth behavior at the early stage of electric current stressing has also been observed in a Sn-based solder joint using an *in situ* synchrotron Laue X-ray microdiffraction analysis [12]. Grain rotation was observed only in the grains located within the current crowding region where there was unbalanced grain boundary energy and thereby the torque necessary for rotation. The grains with high resistivity rotated, which gave rise to lower electrical resistances of the given grains. The grain rotation induced by electric current stressing was ascribed to the anisotropic characteristic of the body-center tetragonal crystal structure of beta-Sn. Al has a face-center cubic crystal structure that exhibits isotropic characteristics for all crystal axes. Therefore, the crystal structure of Al may not attribute to the resistance change, as observed in Fig. 2. In an attempt to explore the mechanism behind these results, the lattice structures of the Al thin films before and after current stressing were investigated by HRTEM as follows.

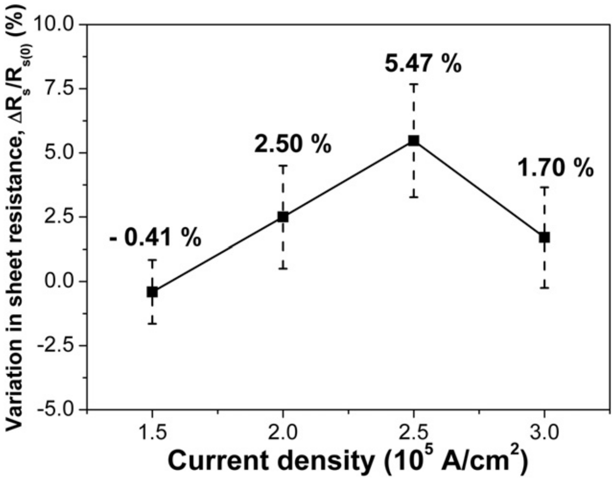

Fig. 2. *Ex situ* variations (%) in the sheet resistance of the Al thin film after current stressing at 1.5–3.0 × 10^5 A cm^{-2} for 1 h.

3.2. Microstructure of the Al thin film prior to current stressing

Fig. 3(a) shows the bright field TEM image of the Al thin film prior to current stressing. The average grain size of the columnar structure was estimated to be 84.74 ± 28.55 nm. The enlargement of the confined region in the Al grain provided a high resolution lattice image, as shown in Fig. 3(b). The FFT diffraction pattern of the selected area along the zone axis [011], inset in Fig. 3(b), presents the Al$(1\bar{1}1)$ and Al(200) orientations. The IFFT treatment of the selected area of Fig. 3(b) was further performed to reveal the lattice structure. The IFFT lattice image, Fig. 3(c), displays a nice atomic arrangement prior to electric current stressing. Fig. 3(d) and (e), respectively, show the IFFT lattice images obtained with a selected orientation treatment for the Al$(1\bar{1}1)$ and Al(200) orientations. It can be seen that there are only few dislocations in the Al thin film prior to current stressing, as represented by the Burgers vectors as shown in Fig. 3(d) and (e). The dislocations result from the intrinsic defects produced during fabrication. The dislocation