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# Elasticity and resistivity study on the electromigration effects observed in aluminum–silicon–copper alloy thin films

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**Abstract**

The early electromigration (EM) processes in the Al–Si(Cu) thin films several tens of nanometers thick deposited on Si reed substrates were investigated by means of the simultaneous anelasticity and electrical resistivity measurements below 360 K. The grain growth, the shortening of $a_\perp$ and the probable lengthening of $a_\parallel$ take place during the EM tests at the current density of $10^8$ A/m$^2$, where $a_\perp$ and $a_\parallel$ denote the atomic plane spacing normal to and the one parallel to the film surface, respectively. The activation energy, $E_{GB}$, for the grain growth is found to be as low as 0.32 eV, possibly suggesting that $E_{GB}$ in very thin nanometer-thick films is much lower than that found in thin micrometer-thick films. The increase in the Young's modulus of the Al–Si(Cu) thin films takes place during the EM tests, suggesting that the grain growth is responsible for it. The decrease in $Q^{-1}$ observed at 330 and 360 K may be explained by a decrease in the grain boundary regions too. The increase in $Q^{-1}$ found during the EM tests at 300 K is possibly associated with an increase in a certain anelastic process in the grain boundary regions.


*Keywords:* Al–Si(Cu); Electromigration; Anelasticity; Resistivity; Grain growth

## 1. Introduction

The demand for downsizing of microelectronic devices is getting continuously strong, where thin metal films as conductors may be used at very high current densities, and the electromigration (EM) effects may govern the reliability of the devices [1–3]. The electrical resistivity measurements have been employed for the reliability studies for the EM failure such as void formation due to mass transport. The more direct measurements of mass transport due to EM have firstly been made by Blech [4–6]. On the other hand, since the microstructure of thin metal films is composed of various diffusion paths such as the grain boundaries, interfaces, and surfaces, various EM processes may be expected, especially for very thin metal films with thickness below 100 nm. In order to get an insight into the underlying EM processes in very thin metal films, understanding of the early EM processes may be important, because changes in the microstructure of thin metal films can be investigated. The anelasticity measurements, as well as the resistivity measurements, may sensitively monitor a change in the microstructure of thin metal films. In the present paper, we carried out simultaneous measurements of the anelastic response and the electrical resistivity about Al–Si(Cu) thin film circuits.

## 2. Experimental

Fig. 1 shows the schematic drawings of a thin film circuit on an Si reed substrate and a measurement setup (see [7,8] for the Si reeds). A change in the resonant frequency $f$ of an Si reed with a uniform thin film, $\Delta f/f$, due to a change in the Young's modulus of the film, $\Delta M'_f/M'_f$, may be given by

$$\frac{\Delta f}{f} = \left(\frac{3b_f}{2b_s}\right)\left(\frac{M'_f}{M_s}\right)\left(\frac{\Delta M'_f}{M'_f}\right), \quad (1)$$

where $M_s$ and $M'_f$ are the Young's moduli of the Si substrate and the film on the substrate, and $b_s$ and $b_f$ denote the thicknesses of the Si reed and the film, respectively [7]. The internal friction $Q^{-1}$ of an Si reed with a uniform thin film may be given by

$$Q^{-1} = Q_s^{-1} + \left(\frac{3b_f}{b_s}\right)\left(\frac{M'_f}{M_s}\right)Q_f^{-1}, \quad (2)$$

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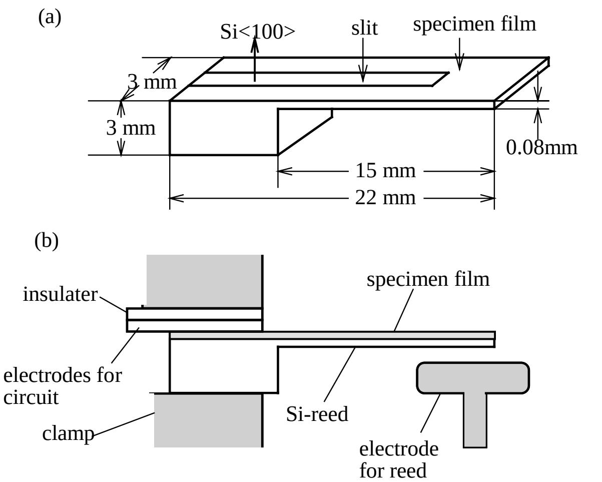


Fig. 1. Schematic drawings for (a) the specimen film circuit on the Si reed substrate and (b) the measurement setup.

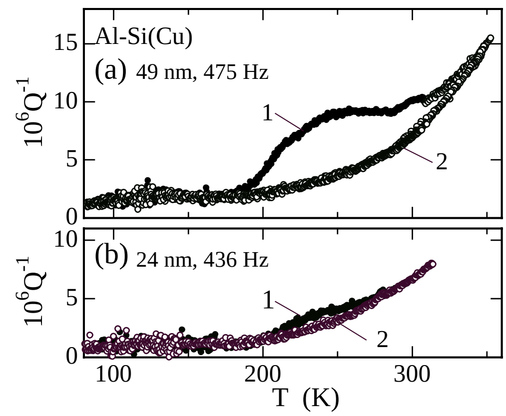


Fig. 2. Examples of the internal friction measurements for the Al–Si(Cu) films with (a) thickness of 49 nm and (b) that of 24 nm. The curves 1 denote the heating run from 80 K to about 300 K just after the deposition. The curves 2 denote the measurement run following the subsequent heating run to (a) 350 K or (b) 315 K after the curves 1.

where $Q_s^{-1}$ and $Q_f^{-1}$ denote the internal friction of the Si substrate and the film, respectively [9,10]. Eqs. (1) and (2) are not correct for the thin film circuit but are employed for convenience here. For the present film with a slit 1 mm wide, $\Delta M_f'/M_f' \sim 2.5 \times 10^3(\Delta f/f)$ and $Q_f^{-1} \sim 1.3 \times 10^3(Q^{-1} - Q_s^{-1})$ for $b_f = 60$ nm and $b_s = 80$ μm. It is noted that $M_f'$ of the present 60 nm thick Al–Si(Cu) film is $73 \pm 3$ GPa and $M_s$ here is the Young's modulus of Si along the ⟨1 0 0⟩ direction, 130 GPa. The temperature dependence of $Q_s^{-1}$ is similar to that reported in [7] but the magnitude of $Q_s^{-1}$ is variable depending on the thermo-elastic damping [11] here associated with the reed thickness.

The Si reed substrate was mechanically polished into a vibrating reed with a thick end for clamping, where all the surfaces of the Si reed substrate were polished to mirror surfaces. The Si reed substrate was chemically etched and then subjected to thermal oxidation for 1 h at 1120 K in a dry $O_2$ gas flow to form an $SiO_2$ surface layer about 10 nm thick. A reed electrode was deposited on the back surface of the Si reed shown in Fig. 1(a) and then a specimen film circuit was deposited on the upper surface. These depositions were made by rf-magnetron sputtering at room temperature in a 6N–Ar gas atmosphere of 0.12 Pa, where the deposition rate was 5 nm/min. The target material was the aluminum alloy containing 1% Si and 0.5% Cu (Al–Si(Cu), hereafter). The thickness of the Al–Si(Cu) film was estimated from an areawise weight of the film, which was separately monitored. After the deposition, silver electrodes for the specimen film circuit were attached and then the Si reed substrate was clamped to the measurement bed (see Fig. 1(b)). The anelasticity and the electrical resistivity measurements were simultaneously made in a vacuum of $10^{-4}$ Pa. For one part of the specimens, conventional X-ray diffraction measurements, and scanning electron microscope (SEM) and atomic force microscope (AFM) observations were made to monitor changes in the microstructure of the Al–Si(Cu) thin films.

## 3. Results

Fig. 2a and b shows examples of the internal friction $Q^{-1}$, measurements for the Si reed substrates with the Al–Si(Cu) film circuits. A very broad $Q^{-1}$ peak between 200 and 300 K is observed just after the deposition, and disappears after heating above 300 K, where the height of the broad $Q^{-1}$ peak between 200 and 300 K varies among specimens. It is noted that a very broad $Q^{-1}$ peak between about 200 and 300 K and its disappearance after heating above 300 K are also observed for the vacuum deposited Ag nanometer-films on Si reed substrates [12]. We surmise that certain anelastic processes in the grain boundary regions are responsible for the very broad $Q^{-1}$ peak. After pre-measurements at about 300 K to remove the broad $Q^{-1}$ peak, the current density $i_d$ was increased to $10^8$ A/m$^2$ and then the EM test was started.

Fig. 3a–d show the changes in temperature $T$, the resonant frequency $f$, $Q^{-1}$, and the electrical resistivity $R$, as a function of the elapsed time $t$, which were observed for the 38 nm thick Al–Si(Cu) film subjected to the EM test with an $i_d$ of $6.3 \times 10^8$ A/m$^2$ at 303 K. At 303 K, $f$ and $Q^{-1}$ increase and $R$ decreases with increasing $t$. Fig. 4a–c denote the $f$ versus $t$ data observed at 303, 330, and 360 K, respectively, for the 38 nm thick Al–Si(Cu) film subjected to the EM test with an $i_d$ of $6.3 \times 10^8$ A/m$^2$. An increase in $f$ is observed in each case, and an amount of the increase in $f$ increases with increasing $T$. Fig. 5a–c are similar to Fig. 4a–c, but here $Q^{-1}$ is plotted against $t$. As already mentioned, $Q^{-1}$ increases at 303 K. On the other hand, $Q^{-1}$ decreases at 330 and 360 K. $R$ shows an exponential decrease with increasing $t$, and the decay time, $\tau_R$, shortens with increasing $T$ (not shown here). Fig. 6 shows the Arrhenius plot for the $\tau_R$ data, where the activation energy $E_R$ is 0.32 eV for the 60 nm thick Al–Si(Cu) film with $8.4 \times 10^8$A/m$^2$ and the 38 nm thick Al–Si(Cu) film with $6.3 \times 10^8$A/m$^2$. Fig. 7a shows examples for the X-ray (1 1 1) reflections observed before and

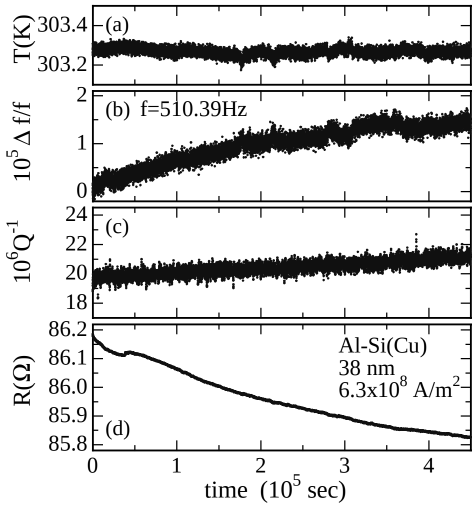


Fig. 3. An example of the EM test for the 38 nm thick Al–Si(Cu) film with $i_d$ of $6.3 \times 10^8$ A/m$^2$ at 303 K: (a) temperature $T$, (b) a change in the resonant frequency $f$, (c) the internal friction $Q^{-1}$, and (d) the electrical resistivity $R$ are plotted against the elapsed time $t$.

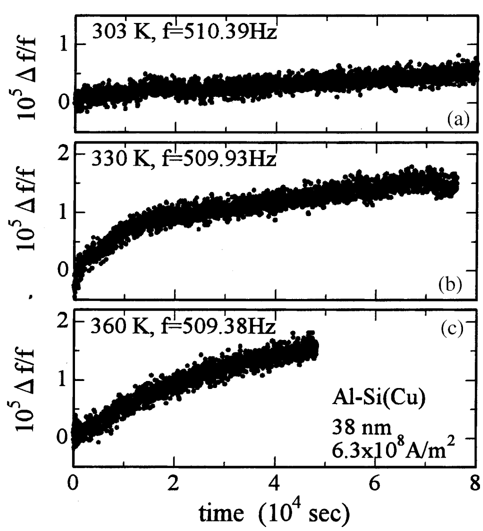


Fig. 4. (a) Redrawing of Fig. 3b. (b) and (c) are similar to (a), but here the data observed at 330 and 360 K are shown, respectively.

after the subsequent EM tests at 300, 330, and 360 K for the 60 nm thick Au–Si(Cu) film with $8.4 \times 10^8$ A/m$^2$ for the total elapsed time of 280 ks, where the $q$ vector is normal to the film surface. It is not shown here but the (1 1 1) reflection is much stronger than the other reflections. In other words, a (1 1 1) texture film dominates. The (1 1 1) reflection $\theta_{(111)}$ increases and the half width $\beta$ decreases after the EM test. Fig. 7b shows changes in $\theta_{(111)}$ observed after the EM tests as a function of $i_d t$.

## 4. Discussion

The AFM images observed for the present Al–Si(Cu) films indicate that the mean grain size is about 30 nm in the

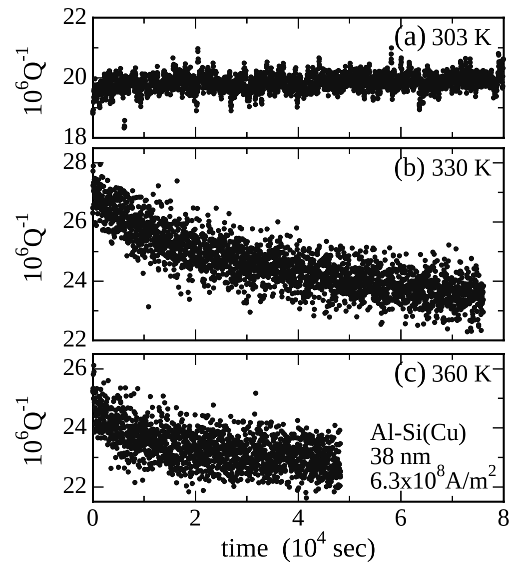


Fig. 5. (a) Redrawing of Fig. 3c. (b) and (c) are similar to (a), but here the data observed at 330 and 360 K are shown, respectively.

as-deposited state and about 50 nm after the EM tests (not shown here). On the other hand, the application of Scherrer's equation to the (1 1 1) reflections shown in Fig. 7a gives that the mean grain size is about 16 and 19 nm before and after the EM tests, respectively. It is suggested that the grain growth takes place and the probable lattice strain is not released during the EM tests. As shown in Fig. 7b, the increase in $\theta_{(111)}$ after the EM tests are commonly observed. On the other hand, a decrease in $\theta_{(111)}$ after the EM tests are reported for Al thin films under the grazing incidence with a very small angle [13]. The combination of these results indicate that the atomic plane spacing, $a_\perp$, normal to and, $a_\parallel$, parallel to the direction of an electric current shortens and lengthens after the EM tests, respectively.

The resistivity changes during the EM tests are composed of a short term, a medium term and a long term in the present

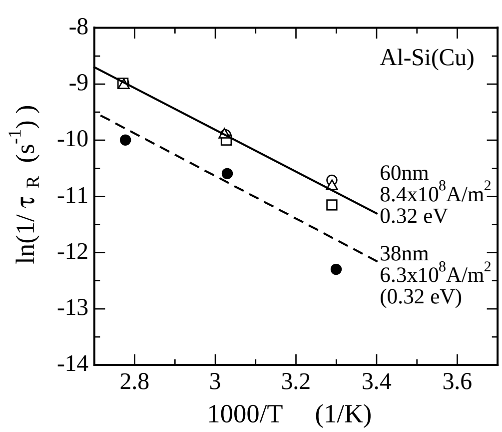


Fig. 6. The Arrhenius plot for the $\tau_R$ data. One specimen for the 38 nm thick Al–Si(Cu) film with $6.3 \times 10^8$ A/m$^2$ and three specimens for the 60 nm thick Al–Si(Cu) film with $8.4 \times 10^8$ A/m$^2$.

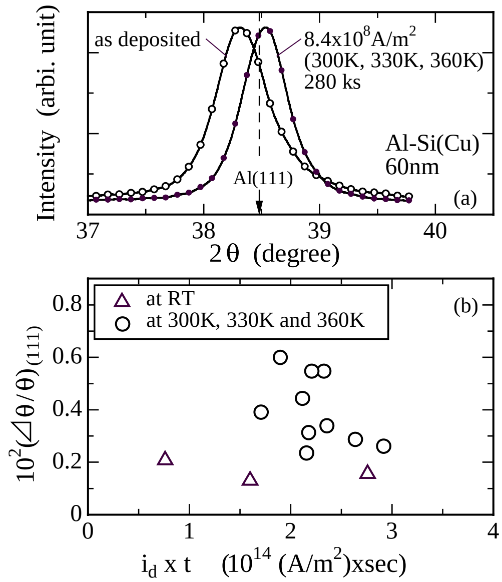


Fig. 7. (a) Examples for the X-ray (1 1 1) reflections observed before and after the subsequent EM tests at 300, 330, and 360 K for the 60 nm thick Au–Si(Cu) film with $8.4 \times 10^8$ A/m$^2$ for 280 ks. (b) Changes in $\theta_{(111)}$ observed for the various Al–Si(Cu) films after the EM tests.

experimental condition (not shown here). The $R$ change seen in Fig. 3d is of the medium term. The short-term change is reversible for the on–off of a current with the relaxation time of the order of $10^3$ s at 300 K, and its $R$ change is much smaller than that for the medium term. The $R$ change for the long term can be detected for the EM tests at 360 K, but is out of the present scope. Fig. 6 shows the Arrhenius plot for the medium term, where the $E_R$ of 0.32 eV found is much lower than the activation energy $E_{GB}$ of 0.6–0.7 eV reported for the grain boundary diffusion and the $E_{IF}$ of 0.8–1.0 eV reported for the interface diffusion [1]. The specific resistivity of the present Al–Si(Cu) thin films is much higher than the bulk value and is explained mostly by the scattering of conduction electrons at the grain boundaries [14]. We surmise that the decrease in $R$ for the medium term here is associated with the grain growth mentioned above, and that the $E_{GB}$ in very thin nanometer-thick films is much lower than the $E_{GB}$ found in thin micrometer-thick films.

The lengthening of $a_{\parallel}$ may take place during the EM tests as mentioned above, and cause a decrease in the Young's modulus along the film surface due to dilatation [15,16]. In contrast, as shown in Fig. 4, the increase in $f$ is found during the EM tests, indicating that the increase in the Young's modulus due to the decrease in the grain boundary regions associated with the grain growth is larger than the decrease in the Young's modulus associated with the lengthening of $a_{\parallel}$. The decrease in $Q^{-1}$ observed at 330 and 360 K may be explained by a decrease in the grain boundary regions too. In contrast, the increase in $Q^{-1}$ is found during the EM tests at 300 K, where the grain growth rate is much lower than that at 330 and 360 K. We surmise that a certain anelastic process in the grain boundary regions increases during the EM tests. Further speculation is premature without more extended experimental data.

## 5. Conclusion

The early EM processes in the Al–Si(Cu) thin films several tens of nanometers thick were investigated below 360 K. During the EM tests at the current density of $10^8$ A/m$^2$, the grain growth, the shortening of $a_{\perp}$ and the probable lengthening of $a_{\parallel}$ take place, where $a_{\perp}$ and $a_{\parallel}$ denote the atomic plane spacing normal to and the one parallel to the film surface, respectively. $E_{GB}$ for the grain growth during the EM tests is found to be as low as 0.32 eV, possibly suggesting that $E_{GB}$ in very thin nanometer-thick films is much lower than that found in thin micrometer-thick films. The increase in the Young's modulus of the Al–Si(Cu) thin films takes place during the EM tests, suggesting that the grain growth is responsible for it. The decrease in $Q^{-1}$ observed at 330 and 360 K may be explained by a decrease in the grain boundary regions too. The increase in $Q^{-1}$ found during the EM tests at 300 K is possibly associated with an increase in a certain anelastic process in the grain boundary regions.

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