Electromigration-induced abrupt changes in electrical resistance associated with void dynamics in aluminum interconnections

Shoso Shingubara[a)]
Toshiba ULSI Research Center, 1, Toshiba-Cho, Komukai, Saiwai-ku, Kawasaki 210, Japan
Hisashi Kaneko
Toshiba R&D Center, 1, Toshiba-Cho, Komukai, Saiwai-ku, Kawasaki 210, Japan
Makoto Saitoh
Tokyo Institute of Technoloqy, 1-12-1, Ohokayama, Meguro-ku, Tokyo 152, Japan

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Electromigration-induced failure mechanisms were investigated by means of extremely sensitive resistance change measurements and simultaneous observations using scanning electron microscopy. Abrupt changes in resistance (ACRs), classified into three types: downward steps, upward steps, and oscillations, were found to occur frequently during the dc current stressing test. It was conspicuously observed that there was a rapid void annihilation associated with an abrupt increase in resistance, and a rapid void formation with a decrease in resistance. ACRs are considered to be caused by a rapid change in the number of excess vacancies concomitant with void annihilations or formations. The thermodynamical analysis on the stability of a void strongly suggests that the change of a local stress from tensile to compressive causes a rapid annihilation of voids, and the opposite one causes a rapid formation. Temperature dependence of the intensity of ACRs exhibited an activation energy of 0.43 eV, which implied that grain boundary electromigration was the driving force of ACRs.

I. INTRODUCTION

Scale shrinkage in very large scale integration (VLSI) demands a higher current density for aluminum interconnections. In this situation, electromigration (EM) has become a key factor which determines the lifetime of interconnections. Many works[1-3] have been devoted to estimate median time to failure (MTF) under certain conditions of grain structures, passivation materials, and stripe geometries. However, it is still very difficult to estimate MTF quantitatively. This entirely owes to the lack of a thorough understanding of void nucleation and growth process. For instance, it has not been well understood how much vacancy supersaturation would be needed for void nucleation, although there have been several investigations which treated void nucleation in terms of vacancy accumulation.[4,5] Therefore a rigorous understanding of electromigration induced void nucleation and growth process experimentally is strongly required.

One of the most effective methods to investigate the EM failure process is *in situ* observation using microscopy. Several works using optical microscopy and scanning electron microscopy (SEM) have revealed that complex dynamical behaviors of voids (void dynamics) determine the lifetime of interconnections.[6,7] It should be noted that void movements toward the cathode direction have been reported by Levine and Kitcher[7] in layered interconnections.

As for electrical methods, resistance change measurements are the most popular ones. The resistance increasing rate has been reported to be almost constant at the early stage of the accelerating test,[8] and measurements of the activation energy by the resistance increasing rate have been accomplished.[8,9] However, it has been recently revealed that the resistance change never increased monotonically but fluctuated with a large randomness during test when the line was narrow.[10] The difference seemed to come from a change in grain structure with linewidth. If the linewidth is as small as the mean grain size, the line shape change due to void formation at the grain boundary seriously affects the resistance change of the total stripe, while only its average behavior appears when the linewidth is much larger than the mean grain size. Recently, current noise measurements, which are the most sensitive ones, have been investigated.[11-13] However, the noise power spectrum indicates the time-averaged behavior of the system and cannot be a tool for investigating void dynamics.

The authors' preliminary works on resistance change measurements of EM have revealed that many abrupt changes in resistance (ACRs) occurred and they increased the randomness of resistance change.[14] The object of this work is to elucidate the characteristics of ACRs and to understand their relation to void dynamics. For this purpose, the authors carried out newly developed extremely sensitive measurements of resistance change and simultaneous observations using SEM, which have never been tried before. Usage of the short stripe enabled the authors to obtain a good correspondence between the resistance changes and void dynamics, such as rapid annihilations and formations.

II. EXPERIMENTAL METHODS

In order to detect an extremely small resistance change of interconnection, we measured voltage fluctuations by a low-noise amplifier (Ithaco 1201) under a constant dc current condition. Figure 1 illustrates the measurement system.

[a)] Present address: Faculty of Engineering, Hiroshima University, Higashi-hiroshima, Japan 724.

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A low-noise resistor R_1 50 times larger than the sample resistance r was directly connected to the sample in order to keep the current constant when the sample resistance fluctuated. The voltage fluctuation between both ends of the interconnection approximately corresponded to the resistance fluctuation of the interconnection by this technique.

An electromagnetically shielded box and batteries were used to eliminate external noise. The voltage fluctuation of the sample was amplified by a low-noise amplifier. An ac coupling with a time constant τ was set between the stripe and the amplifier, so that only the resistance change faster than τ was amplified. τ of 10 or 100 s was used in the experiments. The relation between the net voltage signal $V(t)$ and the signal $\widetilde{V}(t)$ which was ac coupled is expressed as follows:

$$\widetilde{V}(t+\delta t) = [\widetilde{V}(t) + V(t+\delta t) - V(t)] \exp(-\delta t/\tau). \tag{1}$$

$V(t)$ was calculated from the stored data of $\widetilde{V}(t)$ using (1). We were able to detect resistance changes as small as 10^{-7} in ratio using this method.

Unpassivated pure aluminum interconnections were used for the measurements. A 0.8-μm-thick alumnum film was deposited by dc magnetron sputtering onto a thermally oxidized Si wafer. Interconnections were patterned by usual reactive ion etching techniques, and annealed at 450 °C for 15 min in a N_2/H_2 ambience. The stripe size was 2.0 μm in width and 100 μm or 1350 μm in length. The mean grain size after annealing was 2.5 μm. Long interconnections were used only for resistance change measurements. Short interconnections were used for simultaneous observations using SEM and resistance change measurement. A good correspondence between local geometrical change and resistance change by using a short interconnection could be obtained.

An external resistive heater was used for temperature control. The sample temperature was determined by monitoring sample resistance when the temperature rise due to Joule heating effect reached a constant value.

For simultaneous observations using SEM and resistance change measurements, both SEM (JEOL-JSM840) images and voltage fluctuation signals displayed on the screen of the analyzer (Advantest 9404) were recorded in a VTR at the same time.

III. EXPERIMENTAL RESULTS

A. Characteristics of ACRs

A typical example of resistance change during the EM accelerating test until the line is disconnected is shown in Fig. 2. The resistance increase during the first 50 s was due to the Joule heating effect. The resistance change exhibited an increasing tendency with time. However, there were several step-like changes and spikes.

By looking into details, it was found that many abrupt changes in resistance (ACRs) whose magnitude ranged from 10^{-6} to 10^{-2} in the resistance ratio occurred. Further observations revealed that there were three types of ACRs, as shown in Fig. 3. The first was a downward step corresponding to an abrupt resistance decrease [Fig. 3(a)]. The second was an upward step corresponding to an abrupt resistance increase [Fig. 3(b)]. The third was oscillations [Fig.

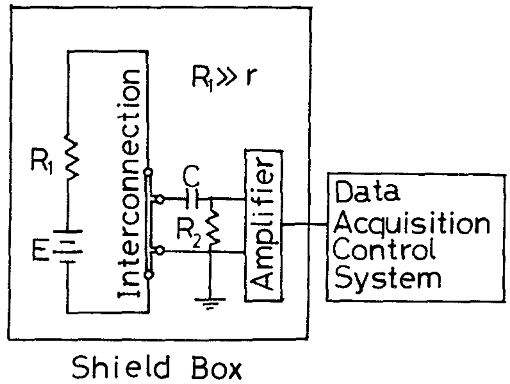

FIG. 1. Experimental system for resistance change measurements. Voltage fluctuations between both ends of the interconnection faster than $\tau(\tau = R_2C)$ were amplified.

3(c)]. The duration of the resistance change in steps ranged between 10 and 100 ms. There was no clear relation between the magnitude of resistance change and the time for changing. Several oscillations were observed in the course of observations for any interconnection. The periods of oscillations varied at each appearance.

Figure 4 shows the occurrences of ACRs during the EM test until the line disconnection. Each type of ACRs exhibited an increasing tendency in magnitude as time passed. At an early stage, the magnitude of the ACRs was below 10^{-5} in resistance ratio. The magnitude increased as large as 10^{-3} when one-half of the lifetime has passed. Downward steps occurred more frequently in the latter half of the lifetime [Fig. 4(a)], while upward steps occurred very frequently at the initial stage [Fig. 4(b)]. Oscillations occurred mostly at the latter half of the lifetime [Fig. 4(c)].

The salient feature of ACRs is intermittence. Sometimes they appeared very often, but later they ceased for a considerably long time. This feature is well elucidated in Fig. 4, where dense areas and sparse areas of ACRs are apparently recognized.

In order to examine the temperature dependence of ACRs, we chose the time average of normalized resistance fluctuation $\Delta R_i/R_0$ due to ACRs, which was expressed as follows:

$$\langle \mathrm{ACR} \rangle = \frac{1}{t_0}\left(\sum_i \left|\frac{\Delta R_i}{R_0}\right|\right), \tag{2}$$

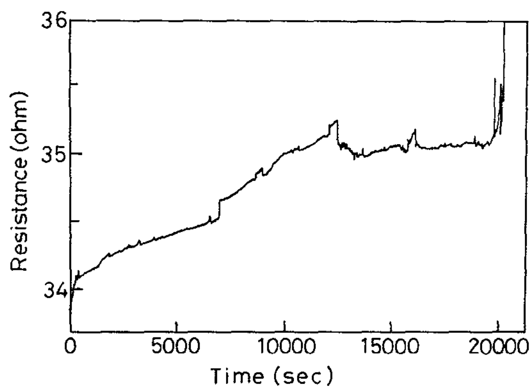

FIG. 2. Resistance change of aluminum interconnection during an EM accelerating test. Current density was 4×10^6 A/cm², temperature was 250 °C. The length of interconnection was 1350 μm.

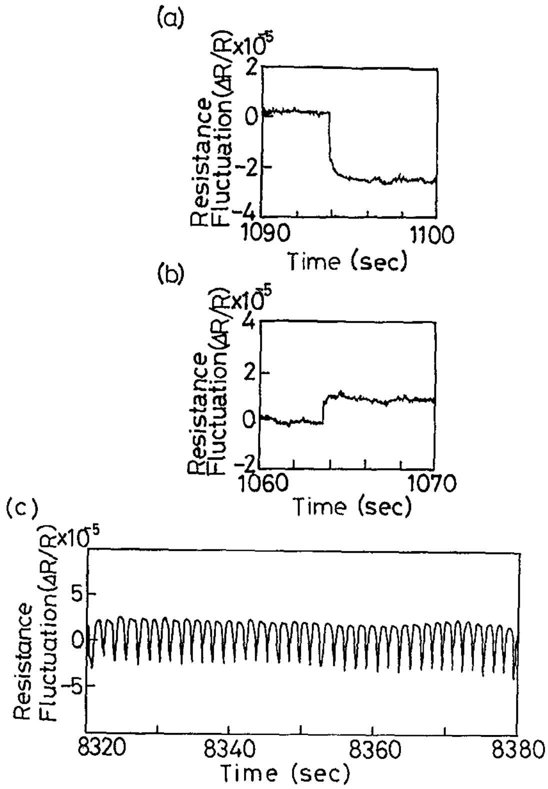

FIG. 3. Three types of ACRs: (a) downward step, (b) upward step, (c) oscillations. Time was counted from the beginning of the EM test. Temperature was 192 °C, and the current density was 4×10^6 A/cm^2. The length of the interconnection was 1350 μm.

where ΔR_i is the resistance change of the ith ACR and R_0 is the initial resistance of the sample. The time t_0 for averaging had to be sufficiently long since the magnitude and the frequencies in ACRs were random. We took t_0 as 1 h from the beginning of the test. Since there were sample to sample variations, ⟨ACR⟩ was averaged over ten samples for each temperature. Figure 5 shows the temperature dependence of ⟨ACR⟩. It is noticeable that ⟨ACR⟩ exhibited an Arrhenius type temperature dependence. The standard deviation of ⟨ACR⟩ for each temperature is indicated by the solid line. The activation energy is 0.43 ± 0.02 eV. This value well coincides with that of the grain boundary diffusion for pure aluminum.[15]

B. SEM *in situ* observations and simultaneous measurements of resistance change

Numbers of ACRs with small magnitude were observed before voids and hillocks grew to a discernible size (500–1000 Å) by SEM. Voids moved to the cathode direction at various speeds concomitant with the change in shape, which agreed with the observation using optical microscopy by Levine and Kitcher.[7] Voids sometimes annihilated or coalesced with each other. These dynamic behaviors were against most of the previous understandings of static EM failure models,[1–5] which treated voids as never moving. Many ACRs were observed during void movements.

It should be emphasized that rapid void annihilations accompanied by a large resistance increase were observed

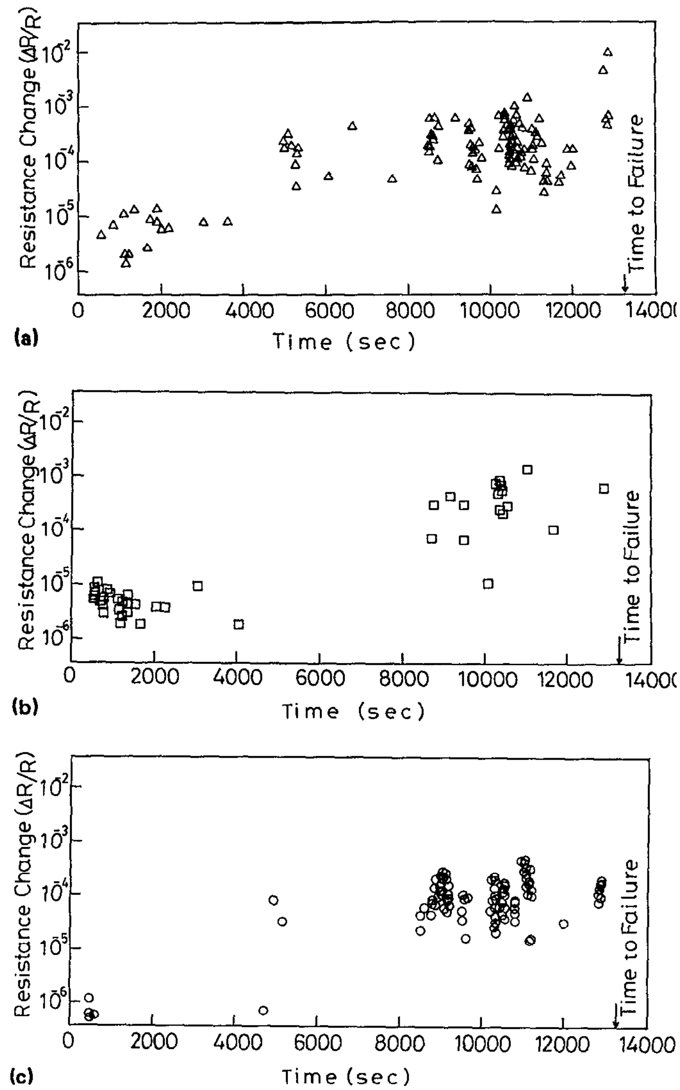

FIG. 4. Occurrences of ACRs through the EM test: (a) downward steps, (b) upward steps, (c) oscillations. Each circle corresponds to one period of oscillation in (c). Temperature was 192 °C, and the current density was 4×10^6 A/cm^2. The length of the interconnection was 1350 μm.

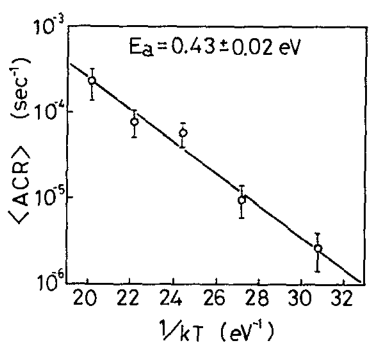

FIG. 5. Temperature dependence of the average resistance fluctuation ⟨ACR⟩ due to ACRs. ⟨ACR⟩ of ten samples were averaged over for each temperature, and the standard deviation of ⟨ACR⟩ for each temperature is indicated by the solid line. The activation energy of ⟨ACR⟩ is 0.43 ± 0.02 eV. Measurements have been carried out at temperatures between 100 and 300 °C. Current density was 3×10^6 A/cm^2. The length of interconnection was 1350 μm.

occasionally. In contrast, rapid void formations accompanied by a large resistance decrease were also observed. Typical examples of rapid void annihilation and formation are shown in Fig. 6. Two voids observed in Fig. 6(a) suddenly annihilated in less than 0.2 s [Fig. 6(b)], and soon afterwards, new voids were formed in a very short time at the cathode side with a distance of 1.5 μm [Fig. 6(c)]. The resistance change during this process is shown in Fig. 6(d). An abrupt increase in resistance amounting to 43% was observed when the voids were annihilated, and a rapid decrease in the initial level was observed when the voids were formed again. This phenomenon gave strong evidence that void dynamics was the origin of ACRs.

When voids gradually changed their shape, the corresponding resistance changes were not so large as that observed during rapid void annihilations and formations. Figure 7 shows a typical example of a gradual change in the void shape. Two notch-shaped voids faced each other, and were connected by a narrow groove [Fig. 7(a)]. The grooved area gradually moved to the cathode direction and grew in width [Figs. 7(b) and 7(c)], and the two voids changed their shape. The corresponding resistance change is shown in Fig. 7(d). The resistance changes during this process were very small and were less than 5% in resistance ratio, which were much less than those of rapid void annihilation observed in Fig. 6. The movement of the grooved area was due to an atom flux across it to the anode direction.

IV. DISCUSSIONS

Experimental results revealed two extraordinary aspects of void dynamics.

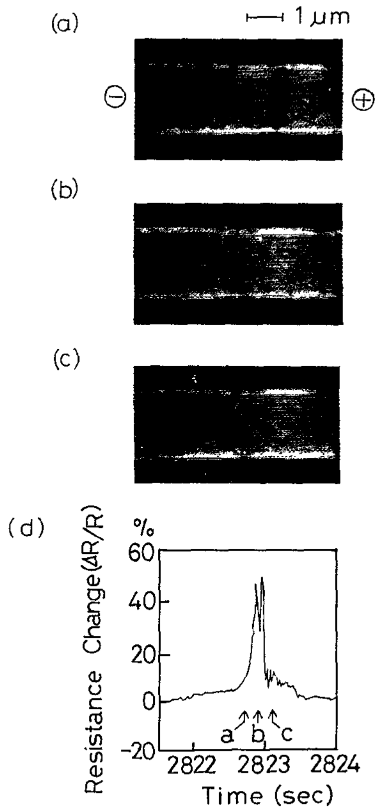

FIG. 6. Observation of rapid void annihilation and subsequent formation by SEM (a)–(c) and corresponding resistance change (d). Arrows indicate times when photographs were taken. Temperature was 200 °C, and the current density was 1.1×10^7 A/cm^2. The length of the interconnection was 100 μm.

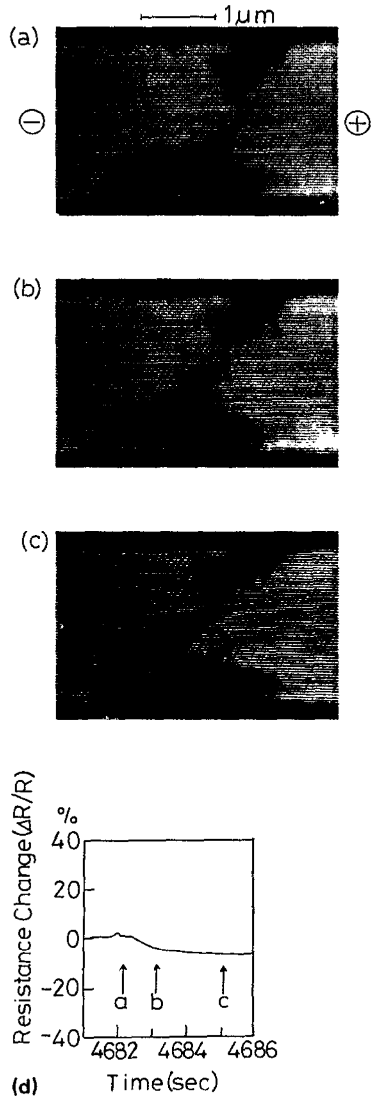

FIG. 7. Observation of gradual change in void shapes (a)–(c) and corresponding resistance change (d). Arrows indicate times when photographs were taken. Temperature was 200 °C, and the current density was 1.1×10^7 A/cm^2. The length of the interconnection was 100 μm.

Firstly, the relation between rapid void annihilation or formation and resistance change shown in Fig. 6 was opposite to the effect of macroscopic shape change on resistance. This can be understood by postulating that voids were decomposed into vacancies when rapid annihilation occurred. The effect of vacancies to an electrical resistivity in FCC metals has been clarified in 1950s both theoretically and experimentally. Controversies on the scattering mechanism of conduction electrons by vacancies have been abandoned, whether or not the lattice distortion surrounding the vacancy[16] or shielded Coulomb interactions[17-19] is dominant. The calculated vacancy resistivities of copper by both methods have nearly the same value.[16,19] Experimentally, a vacancy resistivity of 3 $\mu\Omega$ cm/atom % for aluminum has been reported by Simmons and Balluffi.[20]

The observation in Fig. 6 can be interpreted such that a large number of vacancies were produced by the rapid annihilation of the voids, then they migrated to the cathode direction and gathered again to form voids. Assuming that vacancies produced by void annihilation in Fig. 6(b) amounted to the same volume as the voids in Fig. 6(a), the resistance increase could be estimated to be almost 15% of the 100-μm-long stripe resistance by using the vacancy resistivity of 3 $\mu\Omega$ cm. This estimation is an order of magnitude in agreement with the experimental result (43% increase). The concomitant local vacancy concentration is estimated to almost 10% provided that vacancies produced by the void annihilation existed in an area of 2 μm square. This value is far higher than the thermal equilibrium value (9.2×10^{-6}%) at 200 °C.

On the other hand, if void annihilation is not associated with any vacancy creation and the voids are simply filled with atoms, the interconnection resistance is estimated to decrease by 0.21%, which is inconsistent with the experimental result.

Secondly, why rapid annihilation of considerably large voids should take place?

Blech and Tai[21] have observed a buildup of stress by electromigration. It is possible that stress produced by EM changes when structural deformations such as void and hillock formations and void movements proceed. Therefore, a thermodynamical analysis of the effect of stress on the free energy ΔG for void nucleation has been carried out. The change in the free energy ΔG associated with spherical void nucleation in an equiaxially stressed aluminum lattice is expressed as

$$\Delta G = -(4\pi/3)r^3\sigma + 4\pi r^3 F_s - (1/2)V(\sigma^2/E), \qquad (3)$$

where r is the radius of the void, σ is the stress in the stripe, F_s is the surface energy of the void, V is the volume of the system where the strain energy is relaxed ($5\times2\times0.8\,\mu$m in this case), and E is the Young's modulus of aluminum.[22] The first term in Eq. (3) is the work done by stress on the system, the second is the change in the surface energy of the void, and the third is the change in the strain energy of the system. The sign of the third term changes to plus when the stress becomes compressive.

The results are shown in Fig. 8. It is seen that both the critical radius r_c and the formation energy become small when the tensile stress becomes larger. This means that voids nucleate more easily when the tensile stress becomes larger. When the stress is compressive, G increases monotonically with the radius. This means that no stable void can exist

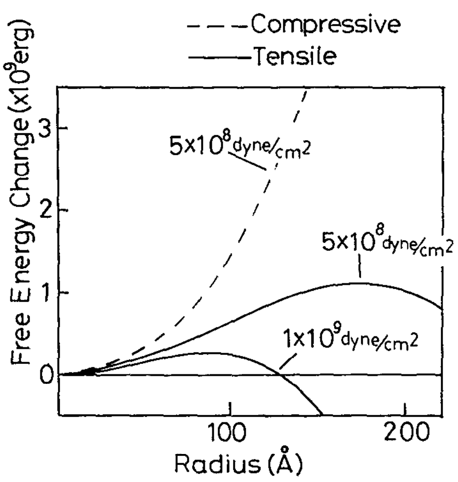

FIG. 8. Change in the free energy associated with void formation in an equiaxially stressed aluminum lattice.

under compressive stress. It is strongly suggested that rapid void annihilation occurs when the stress changes from tensile to compressive, and formation occurs when the stress changes from compressive to tensile. Such a change in local stress may be caused by a change in EM atom fluxes as a result of grain boundary movements or void and hillock formations.

It should be noted that the void annihilation shown in Fig. 6 is much faster than the estimation using the reported value of the self-diffusion constant D. Annihilation of voids will never take place in a time shorter than t_1 ($t_1 = L^2/D$), where L is the void size ($L = 0.5\,\mu$m). Using the literal value of D (5×10^{-14} cm^2/s),[23] t_1 is estimated to be 5×10^4 s, which is five orders of magnitude slower than the experimental results (less than 0.2 s). It is possible that an extremely high vacancy concentration produced during void annihilation supported the enhancement of diffusion.

There have been many works which measured the activation energy of EM grain boundary diffusion by various methods,[9,15,24] and the reported value is between 0.3 and 0.8 eV. Hummel *et al.*[9] reported that the EM grain boundary activation energy increased with increasing temperature from 0.45 to 0.72 eV between 210 and 350 °C. Schreiber discussed that the ideal grain boundary diffusion activation energy is between 0.4 and 0.5 eV, and the broadening resulted from a degree on adjacent grain orientation and annealing conditions.[25] The presently obtained activation energy 0.43 eV for ⟨ACR⟩ is well consistent with Schreiber's estimation and the lower value of Hummel's. Considering that the temperature range of our experiments (100–300 °C) is lower than Hummel's, our results almost agrees with Hummel's. Hence, the driving force of ACRs is considered to be the grain boundary electromigration.

V. CONCLUDING REMARKS

This work reveals new aspects of electromigration-related phenomena. Abrupt changes in resistance (ACRs) are classified into three types: downward steps, upward steps, and oscillations. They are found to occur frequently during direct current stressing tests. The Magnitude of ACRs exhibits an increasing tendency with time, while their occurrences are intermittent. Simultaneous observations using SEM and resistance change measurements reveal that rapid void annihilation is associated with an increase in resistance, and rapid void formation with a decrease. Hence, it is strongly suggested that the upward step corresponds to rapid void annihilation, downward step to rapid void formation, and oscillations correspond to alternations between void annihilation and formation. An increase in resistance associated with rapid void annihilation is explained by the hypothesis that a void is decomposed into vacancies during void annihilation, since a vacancy increases the resistivity by scattering electrons. A thermodynamical analysis of the effect of stress on void nucleation strongly suggests that a change in local stress from tensile to compressive causes rapid void annihilation, and the opposite one causes a rapid formation. Temperature dependence of the intensity of ACRs exhibits an activation energy of 0.43 eV, which suggests that grain boundary electromigration was the driving force of ACRs.

Mechanisms which cause changes in local stress are considered to be changes in EM flux divergences due to grain boundary movements and/or void and hillock formations.

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