Extended Abstracts of the 21st Conference on Solid State Devices and Materials, Tokyo, 1989, pp. 33-36

Electromigration Induced Abrupt Change of Electrical Resistance in Aluminum Interconnection

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Extremely sensitive resistance change measurements of electromigration (EM) and simultaneous SEM observations are performed in aluminum interconnection. It is found that three types of abrupt changes in resistance (ACR) occured during EM; downward step, downward spike and upward step. Experimental results strongly suggest that a downward step corresponds to void formation, and an upward step corresponds to void annihilation. ACR is considered to be caused by rapid change of excess vacancy numbers concomitant with void dynamics. A new accerelating test of EM by the detection of ACR is proposed.

1. INTRODUCTION

Scale shrinkage of VLSI demands higher current density for aluminum interconnections. In this situation, electromigration has become a key factor which determines the life time of interconnections. As the thin film technology develops, it takes much longer time to evaluate MTF (mean time to failure) than before, so that accerelating test of EM endurance is strongly required.

Resistance change methods have been utilized by many authors since early time of EM research. The evaluation of activation energy using the resistance increasing rate[1] turned out to be invalid when the line width became as small as the grain size, because the resistance change exhibited very complicated manner in this region[2]. On the other hand, noise measurements have been recently proposed as a non-destructive and sensitive method[3),4]. We have noticed that abrupt changes in resistance (ACR) were observed when $1/f^2$ noise occured.

In this paper, we focused our attention on ACR for the purpose of understanding EM degrading process. In order to elucidate characteristics of ACR, we accomplished extremely sensitive measurements of resistance change and simultaneous observations using scanning electron microscopy (SEM). These methods enabled us to correlate ACR and the void dynamics exactly.

2. EXPERIMENTAL METHODS

We used pure aluminum films deposited by DC magnetron sputtering onto thermally oxidized Si wafer. We patterned stripes by reactive ion etching, and annealed at 450℃ for 15 minutes in N^2/H^2 ambience. Stripe size was 0.8μm in thickness, 2.7μm in width and 1350μm in length. In order to detect very small resistance change, we used batteries as the current source and low noise amplifier. Figure 1 illustrates the measurement system. In order to keep current density constant, the resistor of 50 times as large as the sample resistance was directly connected to the Al stripe. AC coupling with time constant τ was set between the stripe and the amplifier, so that only the resistance change faster than τ was amplified. We used τ of 10sec or 100 sec in experi-

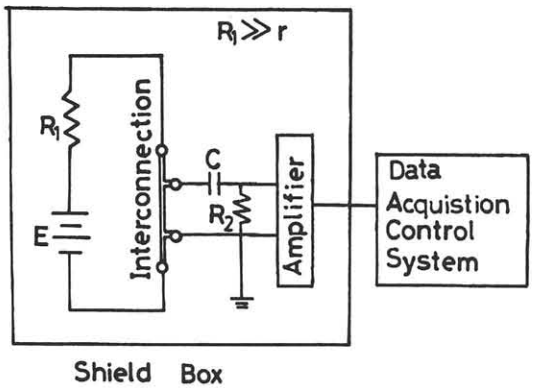

Fig.1 Experimental system of resistance change measurement.

ments. The relation between net voltage signal V(t) and signal $\tilde{V}(t)$ which is AC coupled is expressed as follows.

$$\tilde{V}(t+\delta t)=[\tilde{V}(t)+V(t+\delta t)-V(t)]\cdot\exp(-\delta t/t) \quad (1)$$

We calculated V(t) using the stored data of $\tilde{V}(t)$ from (1). We could detect resistance changes as small as 10^{-7} in ratio by this method.

We also accomplished SEM in-situ observations and simultaneous measurements of resistance change. We used short stripe (100μm in length) in order to get good correspondence between the local geometrical change of stripe and the resistance change.

3.EXPERIMENTAL CHARACTERISTICS OF ACR

Typical example of resistance change during EM test until the line disconnection is shown in Fig.2. The resistance increase during the first 50 seconds was due to joule heating. Then, resistance change exhibited nearly monotonous increase until the failure except two strange behaviors of rapid increase and subsequent decrease at 840sec and 1550sec. When we looked into more detail, we could find lots of ACR whose magnitude ranged from 10^{-6} to 10^{-2} in resistance ratio. By careful measurements, we found that there were three types in ACR as shown in Fig.3. The first was a downward step corresponding to an abrupt resistance decrease (Fig.3-a), the second was a downward spike corresponding to a rapid resistance decrease and recovery (Fig.3-b), and the third was an upward step corresponding to abrupt resistance increase (Fig.3-c). The duration of resistance change of ACR distributed between 10msec and 100msec. Down-

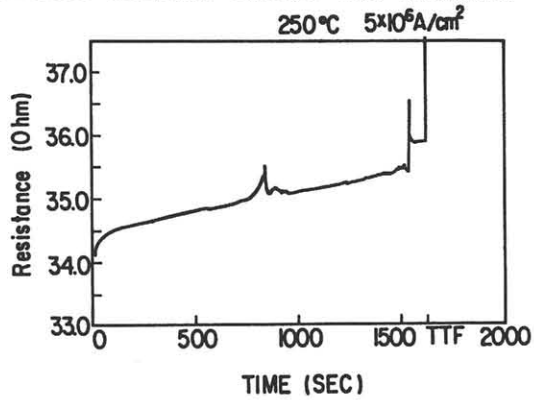

Fig.2 Resistance change of Al interconnection during EM test.

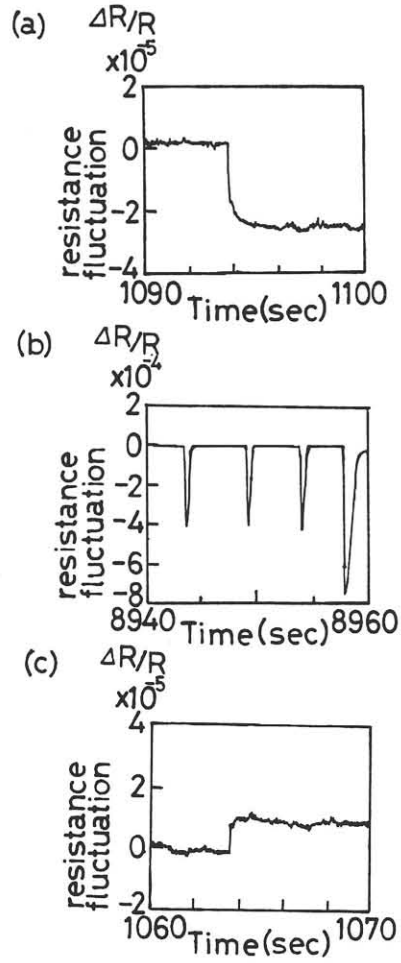

Fig.3 Typical examples of ACR;(a)a downward step, (b)downward spikes and (c)an upward step. Time is counted from the beginning of EM test. 192 ℃, 4×10^{6} A/cm^{2}.

ward spikes had strong tendency to occur periodically.

There are two stages in the behaviors of ACR as shown in Fig.4. During the first stage which was until 30 minutes from the beginning , the magnitude of ACR increased from 10^{-6} to 10^{-3} in ratio. After that (the second stage) it distributed from 10^{-5} to 10^{-2} randomly.

In order to examine temperature dependence of ACR, we chose time average of resistance fluctuation due to ACR; which was expressed as folows.

$$\langle ACR \rangle = (1/t_0) \cdot \sum_i |\Delta V_i| \quad (2)$$

We took enough long time t_0 for averaging. Figure 5 shows temperature dependence of ⟨ACR⟩ at the first stage. Each data is the average value of 5 samples. It is noticeable that ⟨ACR⟩ exhibited Arrhenius type temperature dependence with the activation energy 0.47eV. This value well coincides with that of EM MTF (mean time to failure) for pure aluminum. This suggests that the mechanisms which cause ACR and EM failure are the same.

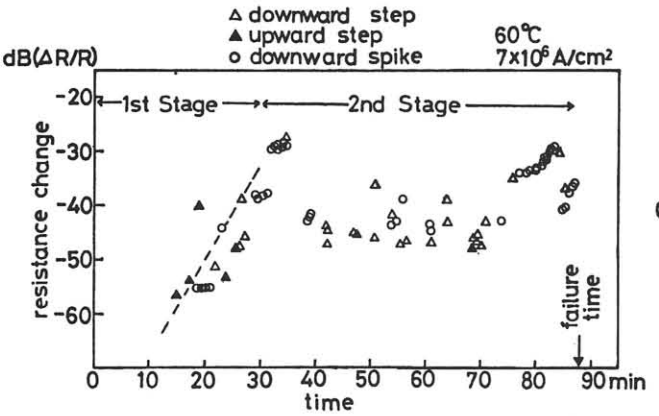

Fig.4 Appearances of ACR during EM test.

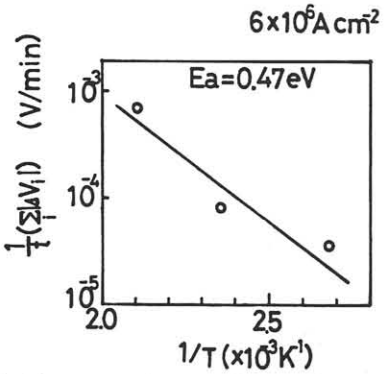

Fig.5 Temperature dependence of the average voltage fluctuation due to ACR.

4.SEM IN-SITU OBSERVATIONS AND SIMULTANEOUS MEASUREMENTS OF RESISTANCE CHANGE

During the first stage of ACR, we observed gradual growth of voids and hillocks. In the second stage, complex phenomena such as void movements , coalescences and annihilations were observed. It was remarkable that a large void which crossed more than a half of the line did not necessarily grew further. It sometimes moved to cathode direction and changed the shape. When void movements or annihilations occured, lots of ACR were observed.

It should be emphasized that a rapid void annihilation accompanied by enormous resistance increase and a subsequent void formation accompanied by resistance decrease were observed as shown in Fig.6. Two voids observed in Fig.6-a suddenly annihilated in less than 0.2 seconds (Fig.6-b), then

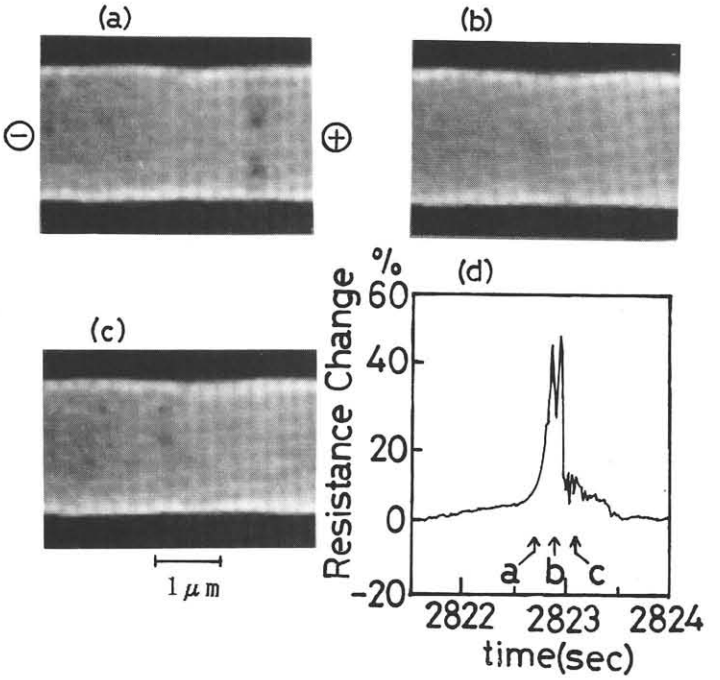

Fig.6 The observation of the void annihilation and subsequent formation (a)-(c) and corresponding resistance change (d). Arrows indicate times when photographs were taken. 200℃,1.1x10⁷A/cm².

new voids were formed in very short time at cathode's side with distance 1.5 μm (Fig.6-c). The resistance change during this process is shown in Fig.6-d. Abrupt increase in resistance amounting to 43% was observed when the void was annihilated, and rapid decrease to the initial level was observed when the void was formed again. This phenomena gave the strong evidence that void dynamics was the origin of ACR.

5.DISCUSSIONS

It is interesting that resistance increased when voids were annihilated. This can be understood by postulating that voids were decomposed to vacancies. It is probable that the resistance increase due to electron scattering by vacancies exceeds the resistance increase by the existance of macroscopic void. By using the value of vacancy resistivity[5] and supposing local increase in vacancy concentration due to void decomposition, void annihilation in Fig.6 can be estimated to almost 7.8% increase in resistance.

It is remarkable that a void of considerable large size annihilates or nucleates in such a short time. We consider that a change of local stress caused an instability of a void. EM induced grain boundary migration or geometrical change due to void and hillock formation may alter flux divergent sites. Subsequently, stress distribution changes.

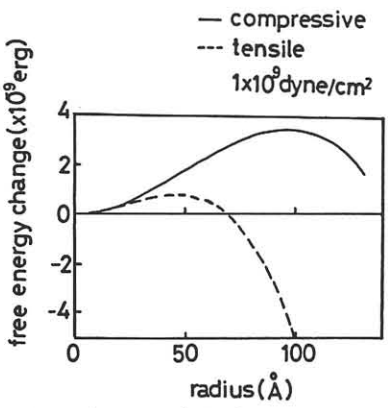

Fig.7 The change in free energy associated with the void formation in stressed Al lattice.

We calculated free energy change of void nucleation in a stressed lattice, which are shown in Fig.7. It is clear that critical radius r_c gets small when the stress is tensile, and it gets large when stress is compressive. It is deduced that a void which gradually grows under the tensile stress will suddenly annihilate when the stress changes to compressive enough.

6.CONCLUSIONS

From our experiments, following conclusions are obtained.

(1) We found that three types of abrupt changes in resistance (ACR);a downward step, downward spikes and an upward step.

(2) An upward step corresponds to rapid void annihilation, and a downward step corresponds to rapid void nucleation.

(3) Temperature dependence of ACR is Arrhenius type with the activation energy 0.47eV.

(4) A detection of ACR enables us to predict the EM endurance in a very short time.

ACKNOWLEDGEMENT

The authors would like to express gratitude to Prof. T.Kawakubo (T.I.T) and Mr.M.Kashiwagi (Toshiba) for meaningful discussions and encouragements.

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