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Pulsed Current Electromigration Mechanism —Instantaneous Temperature Profile Model

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Electromigration of aluminum interconnections under pulsed current stress is investigated. The mean time to failure (MTTF) is reported to improve in the high frequency region. To clarify its mechanism, samples with different thermal chracteristics are examined. The synchronized measurement of the sample temperature reveals that the MTTF improvement in the high frequency region is due to the lowering of the effective temperature while the pulse is on.

1. INTRODUCTION

Electromigration under pulsed current stress has become an important subject for establishing the reliability of sub-micron feature size Al alloy interconnections for ULSIs. The mean time to failure (MTTF) has been reported to change depending on the frequency of the pulsed current in a high current density region (the pulse height is about 10^7 A/cm^2) [1, 2]. This current density is extremely high comparing with the ordinary electromigration tests. However, in these works, the influence of such an extremely high current density was not sufficiently taken into account. For example, in such a high current density region, the self-heating of the conductor line becomes remarkable and the sample temperature may vary significantly according as the pulse is on or off. Therefore, the effect of the variation profile has to be estimated. This paper clarifies the mechanism of the MTTF dependence on frequency by investigating the instantaneous temperature profile of a conductor line under pulsed current stress.

2. EXPERIMENTAL

SAMPLE PREPARATION

Two groups of test devices were prepared for comparison. In one group, 0.7μm-wide and 0.5 μm-thick Al-1%Si lines were fabricated on oxidized Si (this group is referred to as Al/SiO$_2$), and in the other group, 0.7 μm-wide and 0.9 μm-thick Al-2%Si lines on 2 μm-thick polyimide (PIQ) layers (Al/PIQ). The reason why PIQ was used lies in its extremely small heat conductivity (Table 1). This small conductivity makes the thermal relaxation time of a PIQ layer about one hundred times as large as that of a SiO$_2$ layer. This is expected to affect the thermal response of the samples.

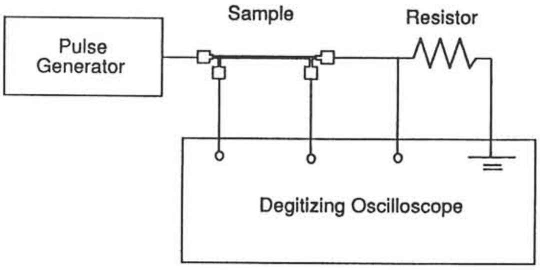


Fig. 1. Pulsed current stressing circuit. The resistor is used to monitor the current.

	Thickness (μm)	Density (g/cm^3)	Specific Heat (J/g°C)	Heat Conductivity (W/cm°C)	Thermal Relaxation Time (s)
SiO_2	0.5	2.27	1.0	0.014	4.1×10^{-7}
PIQ	2.0	1.4	1.1	0.0017	3.3×10^{-5}

Table1. Heat conduction characteristics of the insulator underlying the conductor lines. One-dimentional thermal relaxation times in vertical direction calculated from these data are also shown in this figure.

STRESSING METHOD

A uni-directional pulsed current was applied, and synchronized voltage measurements were taken by using a circuit shown in Figure 1. The stressing was performed at the room temperature. The test conditions were as follows: the frequency was 100 Hz-10 MHz, the duty cycle was 50 %, and the peak current densities of Al/SiO_2 and Al/PIQ were 2.3×10^7 A/cm^2 and 7.0×10^6 A/cm^2, respectively. The rising time of the pulsed current was about 5 nano-seconds; the pulse stress could be applied until about 10 MHz with negligible distortion. At 10 MHz, 20% of a pulse period was distorted, as shown in figure 2.

SAMPLE TEMPERATURE MEASUREMENT

The sample temperature was calculated from the sample resistance monitored by a digitizing oscilloscope [3]. The sample temperature while the pulse was off was measured by applying nearly 5 % of the peak current density. The temperature change due to this additional current was estimated as a few degree. The temperature coefficient of the sample resistance used for the calculation was measured separately using a furnace.

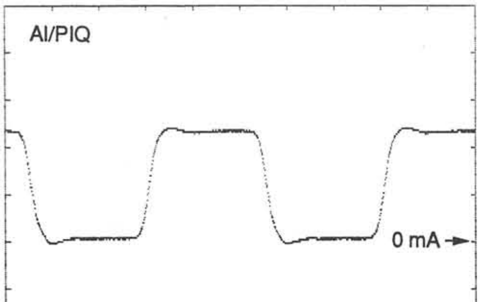


Fig. 2. Waveform of uni-directional pulsed current at 10 MHz.

3. RESULT AND DISCUSSION

The MTTF dependence on frequency was first examined. For both groups of samples, the MTTF was observed to improve by about two orders of magnitude in the high frequency region, as shown in Figure 3. However, the MTTF dependence on frequency differs depending on the sample structure; the frequencies at which the MTTF begins to increase are about 20 kHz (Al/SiO_2) and 2 kHz (Al/PIQ), respectively. The former agrees with those measured for similar samples by Miller[1] and Noguchi et al[2]. In the case of Al/SiO_2, the MTTF improved monotonously in the measured range, but in the case of Al/PIQ, saturation is found in the over 400 kHz region. The MTTF improvement of Al/PIQ in the high frequency region amounts to 8×10^1.

Secondly, the temperature profiles during a pulse period were investigated. The typical temperature profiles during a pulse period are shown in figures 4 (a) and (b). From these results, the following characteristics are pointed out. First, the profile of the conductor temperature is regarded as an exponential type with a thermal relaxation time which depends on the sample structure. Next, the temperature in the high frequency region is over 100 °C

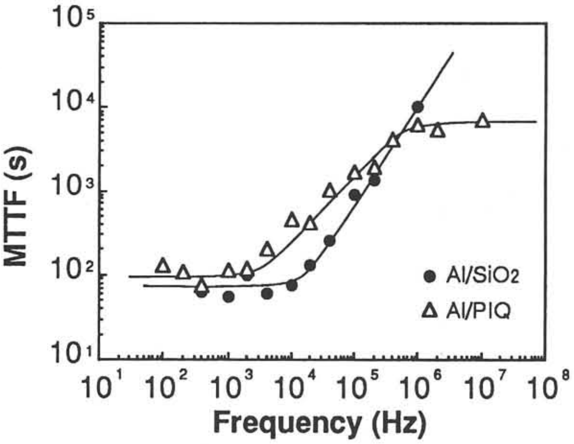
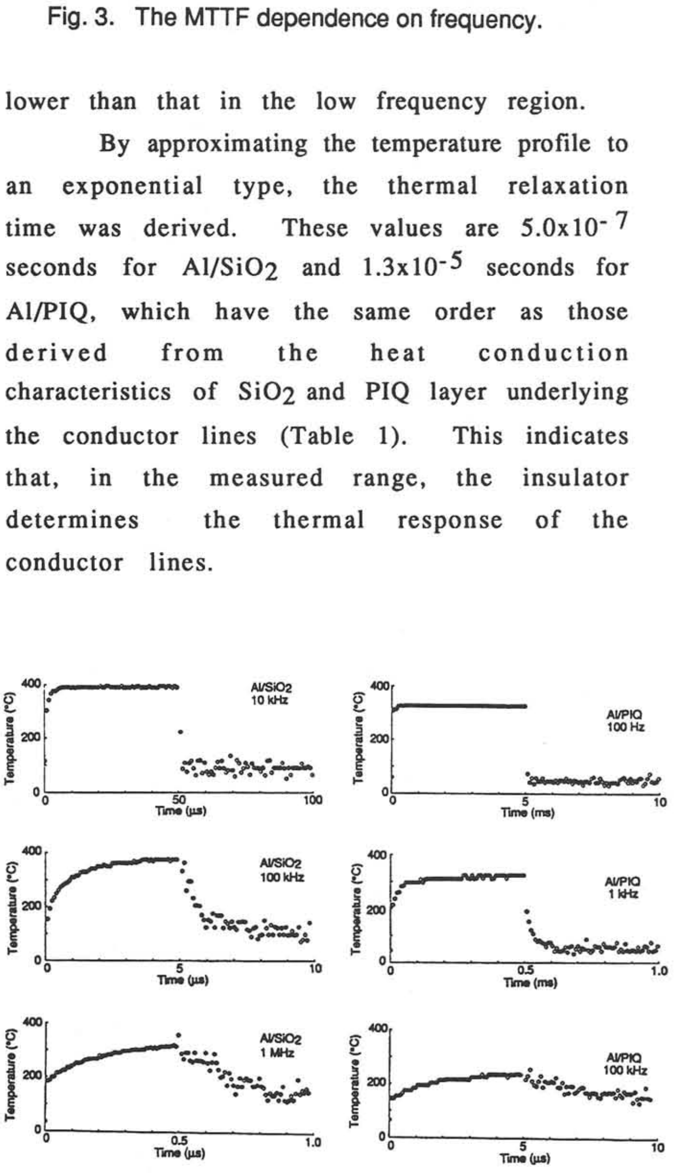


Fig. 3. The MTTF dependence on frequency.

lower than that in the low frequency region.

By approximating the temperature profile to an exponential type, the thermal relaxation time was derived. These values are $5.0x10^{-7}$ seconds for Al/SiO_2 and $1.3x10^{-5}$ seconds for Al/PIQ, which have the same order as those derived from the heat conduction characteristics of SiO_2 and PIQ layer underlying the conductor lines (Table 1). This indicates that, in the measured range, the insulator determines the thermal response of the conductor lines.



(a) Al/SiO2

(b) Al/PIQ

Fig. 4. Instantenous temperature profile of the conductor and its dependence on frequency. (a) Al/SiO_2 (b) Al/PIQ

Whether the half of a pulse period is longer or shorter than the relaxation time determines the behavior of the sample temperature. The frequencies (refered to as f_0) for Al/SiO_2 and for Al/PIQ derived from the relaxation times are 1.0 MHz and 38 kHz, respectively. If the pulse period is much longer than the relaxation time (low frequency region), the temperature precisely follows the pulsed current. As the frequency increases, the temperature profile distorts (transient frequency region), and eventually converges into a constant value line (high frequency region).

The temperature differences while the pulse was on between the high and low frequency region were 156 °C (Al/SiO_2) and 145 °C (Al/PIQ), respectively. Here, the former was an extrapolated value, because the temperature convergence wasn't observed in the measured range.

Thirdly, the MTTF improvement by the lowering of the temperature in the high frequency region was estimated. The following assumptions were made; the electromigration damage per unit time has an Arrhenius type temperature dependence. The electromigration damage was calculated by summing up the amount of each moment ($\propto \exp[-Qa/kT(t)]$) during the pulse-on periods. Here, the value of activation energy (Qa) for the grain boundary diffusion of Al (0.5 eV) was used for T<275 °C, and that for the lattice diffusion (1.5 eV) was used for T>275 °C. k is the Boltzmann constant.

To clarify the effect of the temperature profile, a constant temperature at which the damage is equivalent to the calculated damage was defined (referred to as the effective temperature). The calculated MTTF and the effective temperature are shown in figures 5 (a) and (b), as the functions of frequency. The experimental results shown in figure 3 are also plotted in the same figures for comparison. It is

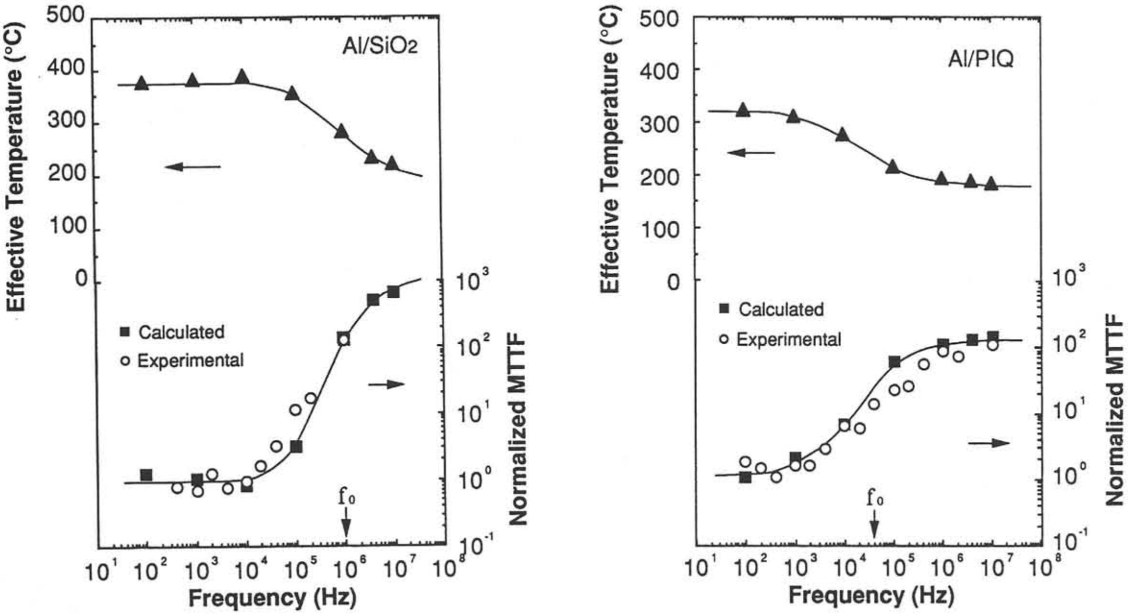


Fig. 5. The effective temperature and the MTTF calculated from the temperature profile. The measured MTTF are also plotted for comparison. f_0 is the frequency at which the half of a pulse period is equal to the thermal relaxation time of the sample.

revealed that this model gives a consistent explanation for the difference in frequencies at which the MTTF begins to increase, and the saturation of the MTTF improvement for Al/PIQ in the over 400 kHz region. The calculated amount of the MTTF improvement for Al/PIQ is about $1.3 \mathrm{x} 10^2$, which is about the same order of the observed improvement. The saturation of MTTF improvement for Al/SiO$_2$ will be observed in the over 100 MHz region, if a pulsed current could be applied up to 100 MHz without distortion.

4. CONCLUSION

It is clarified that the MTTF improvement in the high frequency region is due to the lowering of the effective temperature while the pulse is on, and that the critical frequency depends on the heat conduction characteristics of the insulators underlying the conductor lines.

This work revealed that, when the instantaneous temperature profile during a pulse period is taken into account, the electromigration under pulsed current stress can be described by the similar model for DC current stress about the MTTF dependence on temperature.

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