EFFECTS OF HIGH CURRENT PULSES ON INTEGRATED CIRCUIT METALLIZATION RELIABILITY

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Abstract

Transient heat flow analysis using 2-dimensional finite element method has been used to calculate the temperature rise of aluminum lines on passivated and unpassivated silicon substrates. The results are used to predict the effect of self-heating on electromigration lifetime of aluminum interconnects under pulsed current stressing. A model has been developed to incorporate damage relaxation and self-heating effects on electromigration. We have shown that self-heating is expected to produce less than 20% error in typical accelerated testing conditions provided the peak current density (J_p) is less than $4\times10^6 A/cm^2$. Design rules based on keeping the average current density (J_{av}) constant is acceptable provided that duty factor is larger than 1% for all frequencies above 1 MHz.

Introduction

The median time-to-failure (MTF) of a conductor under constant current stressing is commonly expressed by the Black's equation [1] as:

$$\mathrm{MTF}_{dc} = AJ^{-n}\exp\left(\frac{E_a}{kT}\right) \quad (1)$$

A is a constant dependent upon the geometry and microstructure of the film, J is the current density, n is a constant typically 2, E_a is the activation energy typically $0.5eV$, k is the Boltzmann's constant and T is the conductor temperature. From Eq.1, we see that MTF is halved if T increases from 25°C to 36°C or from 175°C to 200°C.

Accelerated life testing of Al interconnect often are performed using constant dc current densities exceeding $1\times10^6 A/cm^2$. In most studies, the effect of self-heating on the conductor temperature is taken into account when extracting the E_a and n in Eq.(1). Integrated circuits interconnect, however, often carry short and high current pulses. The extrapolation of dc MTF results to pulsed dc operation condition is not straightforward. At a given peak current density, MTF measured in total pulse-on time is lengthened due to relaxation effect during pulse-off time. In addition, thermal cycling effect reduces self-heating because of heat conduction in the pulse-off cycle. The temperature rise is therefore related to the pulsewidth, duty factor and peak current density, as well as the device structure.

In this paper, we present a model which incorporates the damage relaxation and thermal cycling effects in electromigration failure of Al lines. Our model gives the frequency and duty factor dependence of pulsed dc median time-to-failure. The objective of our work is to predict pulsed dc lifetime using constant dc stressing results.

Simulation and Model

Simulation of transient heat flow for an Al line on SiO_2/Si substrate has been performed using two-dimensional finite element method. The temperature distribution of the structure (see Fig.1) at various times can be calculated when the Al line is powered by a train of rectangular current pulses. We have used constant heat conductivities and heat capacities for the various materials in our simulation. The temperature dependence of Al resistivity is neglected in our calculation because the effects are negligible for the temperature range (100°C-300°C) of interest.

The temperature contour map of the cross section of the device is shown in Fig.1. We have assumed that the interconnect has sufficient length that it can be treated as semi-infinite. The boundary conditions used in thermal simulation of the structure in Fig.1 are: negligible heat conduction between air and the structure, heat conduction across the left and right sides, 5μm from the Al line (see Fig.1) is zero, and the temperature of the lower side of the structure, 20μm below the Al line is held constant at the ambient temperature of 25°C. The simulation result for $J_p = 1\times10^8 A/cm^2$ with frequency at 10 MHz and Duty Factor = 10^{-3} is shown in Fig.1. The temperature of the Al line is uniform owing to its large thermal conductivity and most of the temperature gradient is found in the SiO_2 region.

In the transient analysis, time steps are chosen to give 5% or less error in the temperature calculation. Fig.2 shows that steady state condition is attained after a few thermal characteristic time (τ_T) have elapsed. From Fig.2, we can estimate the characteristic time, $\tau_T \approx 1\mu s$ which agrees with the approximate calculation from the thermal conductance and thermal capacitance of the structure.

The median-time-to-failure (total test time) of Al line under pulsed dc current stressing has been shown to follow the expression [2]:

$$\mathrm{MTF} = AJ_{av}^{-2}\exp\left(\frac{E_a}{kT}\right) \quad (2)$$

The use of the average current density J_{av} in place of the dc current density J_{dc} in the original Black's equation (Eq.(1)) is derived from the vacancy relaxation model described in [2] where Eq.(2) is shown to be valid for pulse period much shorter than the damage relaxation time ($\tau_d \approx 1ms$). According to Eq.2 and Eq.1 with n = 2, the enhancement factor for pulsed dc MTF (total test time) for a fixed peak current density J_p is:

$$\mathrm{MTF}/(\mathrm{MTF})_{dc} = (\text{Duty Factor})^{-2} \quad (3)$$

Rewriting Eq.(2), we obtain:

$$A = \mathrm{MTF} \times J_{av}^{2}\exp\left(\frac{-E_a}{kT}\right) \quad (4)$$

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If we assume the "average" electromigration damage to the line is proportional to the time t it has been powered, we can write the "average" rate of incremental damage $D(t)$ as:

$$D(t) = J_{av}^{2}\exp\left(\frac{-E_a}{kT(t)}\right) \tag{5}$$

And the time-to-failure is found from

$$\int_0^{\mathrm{MTF}} D(t)dt = A \tag{6}$$

where we have used the time variation of the line temperature (Fig.2) and $0.5eV$ for E_a in Eq.(6).

Effects on Accelerated Pulse Test Data

We have compared simulation results with experimental data by Brooke [3] and Miller [4]. Table I summarizes their pulsed dc experiments. In Fig.3, we plot Brooke's results along with our simulation results. The temperature rise above ambient is very small for Brooke's structure. As a result the calculated MTF with the inclusion of self-heating differs negligibly from MTF obtained by Eq.(2) using the ambient temperature T=25°C (Fig.3). We have also plotted the MTF as a function of duty factor assuming no damage relaxation. In this case, the MTF (total test time) is:

$$\mathrm{MTF} \propto J_{rms}^{-2} \tag{7}$$

where J_{rms} is the root-mean-square value of the current density.

We can see that Eq.7 underestimates the lifetime in Fig.3 whereas Eq.2 fits the experimental data fairly well. Therefore, the use of Eq.2 for our MTF calculation is justified.

In Fig.4, we compare Miller's data with the simulation results. The self-heating effect in Miller's structure is not negligible as shown by the correction in MTF when heating is included. Self-heating is more prominent here because Miller used a higher current density ($J_p = 4\times10^6 A/cm^2$) and the Al line was not passivated. Our simulation results indicate passivation will significantly reduce self-heating effect.

The correction factor found in our calculation enhances MTF (see Fig.4). The MTF is shown to be better for lower duty factor because Al interconnect powered by pulses (with $J_p = J_{dc}$) receives less power per cycle and is cooler than interconnect powered by constant dc current. For example, at 0.25 duty factor, the average Al temperature is about 6°C lower than for 1.0 duty factor. Therefore MTF/(MTF)$_{dc}$ is about 20% higher when the heating effect is included than when it is not.

For these comparisons with accelerated test data, we conclude that self-heating has a relatively minor effect on MTF with $J_{av} < 10^7 A/cm^2$.

Effects on Design Rule

The quoted design rule for integrated circuit interconnect is $J_{av} = 1\times10^5 A/cm^2$. In Fig.5, we demonstrate the expected effect of self-heating at small duty factors. MTF found for the structure shown in Fig.1 has been normalized against the dc MTF of line powered by $J_{dc} = 1\times10^5 A/cm^2$ at the ambient temperature of 25°C. The peak current density of the rectangular pulses is increased as duty factor is reduced to keep $J_{av} = 1\times10^5 A/cm^2$. We observe that when $J_p < 1\times10^8 A/cm^2$ (i.e. duty factor > 10^{-3}), self-heating effect is not important and constant J_{av} rule is acceptable. For $J_p > 1\times10^8 A/cm^2$, self-heating starts to become important and degrades the interconnect lifetime. In the extreme case, picosecond current pulses of $1\times10^{10} A/cm^2$ can cause melting of the Al line.

For future generations of integrated circuits, the current pulse frequency will increase while the duty factor is likely to remain unchanged (e.g. CMOS operation). It is important to investigate the validity of the J_{av} design rule as frequency increases. We have found in our calculation that as the frequency increases with $J_{av} = 1\times10^5 A/cm^2$ and Duty Factor = 0.01, the lifetime of the interconnect improves slightly (Fig.6). The enhancement in MTF levels off for pulse period much shorter than the thermal characteristic time (~ 1 μs). This observation is explained by the fact that for short pulsewidth, the time variation of line temperature follows a triangular waveform while for long pulsewidth, it is approximately a rectangular waveform. At very high frequencies, the temperature excursion during each cycle will become small because the structure has not enough time to respond to the current pulses. On the other hand, at very low frequencies, the Al line is essentially powered by a dc current of $1\times10^7 A/cm^2$ and self-heating makes the Al temperature about 75°C higher than at 10 MHz.

Conclusion

We have developed a model relating pulsed dc electromigration lifetime to constant dc electromigration lifetime which incorporates the self-heating and damage relaxation effects. The importance of self-heating in interconnect reliability depends on the geometry of the interconnect and the current densities in the line. We have shown that for the current densities used in accelerated life testing, self-heating can be neglected for passivated lines. However, for peak current densities in excess of $4\times10^6 A/cm^2$, temperature rise in the line can become noticeable and may have to be taken into account in MTF calculation. With self-heating effect included, design rules based on keeping J_{av} constant is acceptable provided that duty factor is larger than 1% for all frequencies larger than 1 MHz.

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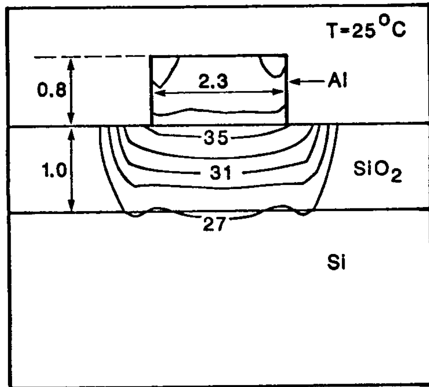

Fig.1. Example of structure used for transient thermal simulation: the aluminum line is on top of 1 μm SiO_2 on Si. The ambient temperature is 25 °C. The contour shows the temperature of the structure for Al line powered by 10 MHz rectangular pulses with $J_p = 1\times10^8 A/cm^2$ and Duty Factor = 1×10^{-3}. The temperature is essentially uniform in Al and most of the gradient is found in SiO_2. The dimensions shown are in μm.

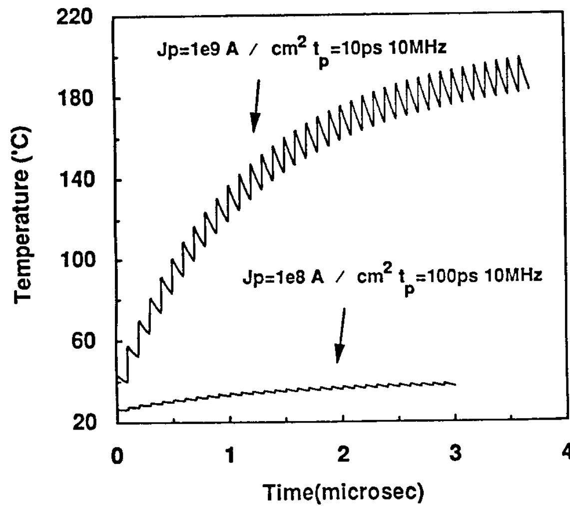

Fig.2. Time variation of the temperature of the Al line simulated for the structure shown in Fig.1. The temperature approches a steady state waveform after a few thermal characteristic time τ_T.

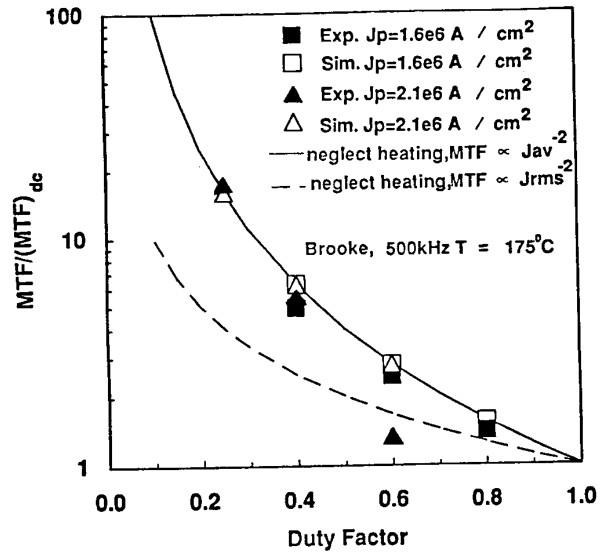

Fig.3. Comparison of simulation results with Brooke's data [3]. The MTF plotted is normalized against the constant dc MTF with $J_{dc} = J_p$. The effect of self heating is negligible because the samples were passivated and the current density used was small. Also shown is the agreement of experimental MTF with a damage relaxation model which uses J_{av}^{-2} in Black's equation (Eq.1).

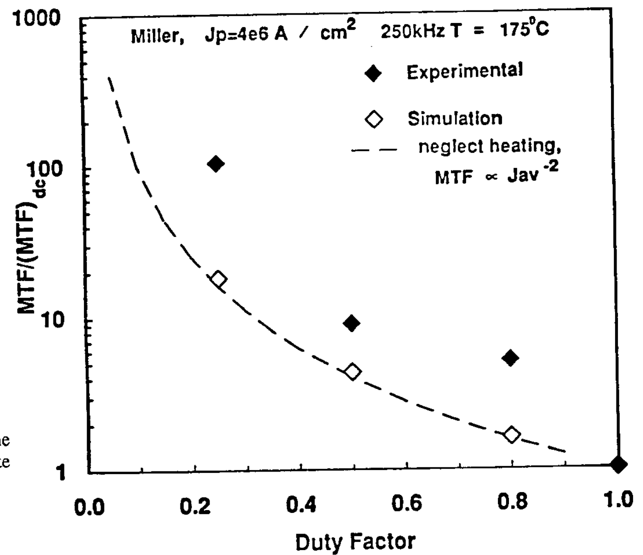

Fig.4. Comparison of simulation results with Miller's data [4]. The effect of self heating causes a slight improvement in MTF for pulsed dc stressing. The samples were not passivated and the current density used was $4\times10^6 A/cm^2$.

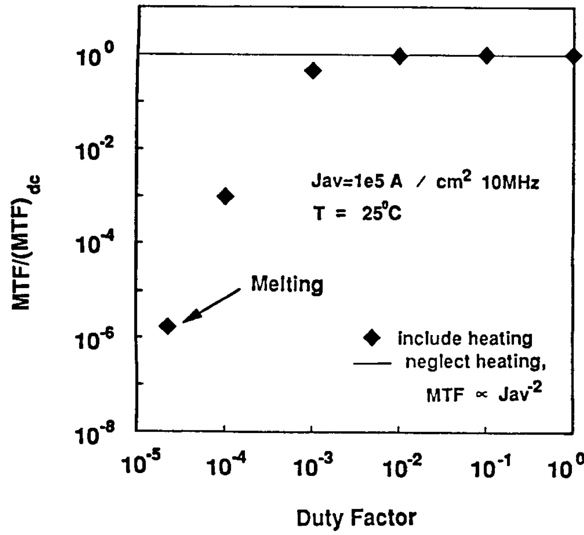

Fig.5. Normalized MTF calculated for structure shown in Fig.1 as a function of duty factor. The current density for all the points is fixed at $J_{av} = 1{\times}10^5 A/cm^2$ with frequency at 10 MHz. Assuming no self-heating, MTF is simply a straight line according to Eq.2. From the results, we see a rapid degradation of lifetime when $J_p > 1{\times}10^8 A/cm^2$ for pulses shorter than 100 ps.

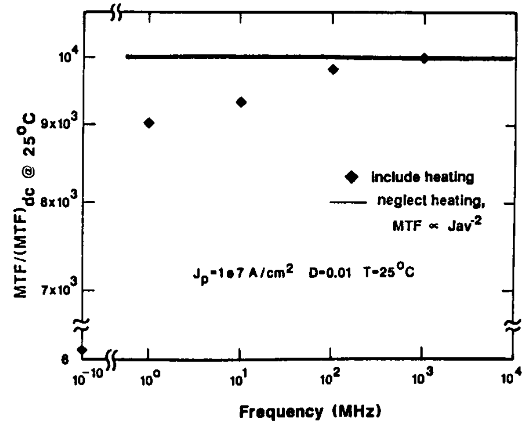

Fig.6. MTF calculated for structure shown in Fig.1 as a function of frequency. MTF is normalized to dc MTF for $J_{dc} = 1{\times}10^5 A/cm^2$. The peak current density is fixed at $J_p = 1{\times}10^5 A/cm^2$ and the duty factor is 0.01. MTF improves slightly at higher frequency because of less self-heating when the pulsewidth is much shorter compared to the thermal characteristic time τ_T. At the extreme of low frequency, the calculated MTF is just the constant dc MTF for $J_{dc} = 1{\times}10^7 A/cm^2$, multiplied by the enhancement factor due to damage relaxation.

Material	Thickness	Passivation	$J_p (A/cm^2)$	Temperature(°C)	Frequency	Reference
Al-1%Si	0.7µm	Glass	1.6 and $2.1{\times}10^6$	175	500kHz	Brooke [3]
Al	0.4µm	No	$4{\times}10^6$	175	250kHz	Miller [4]

Table 1. Summary of experimental results used for comparison.