

EFFECTS OF SELF-HEATING ON INTEGRATED CIRCUIT METALLIZATION LIFETIMES

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Abstract

Interconnect electromigration lifetimes under pulse DC (uni-directional) current stress have been shown to follow the Black's equation [1]:

$$TTF = \frac{A \exp(E_a/kT)}{J_{ave}^2} \quad (1)$$

where TTF is the time-to-failure of the interconnect, A is a constant dependent upon the geometry and microstructure of the film, k is the Boltzmann's constant, T is the interconnect absolute temperature, E_a is the activation energy ($\approx 0.5eV$ for aluminum interconnect), J_{ave} is the average current density. From Eq.(1), we see that the electromigration lifetime is related exponentially to reciprocal temperature, thus the increase in the metal line temperature can cause a significant reduction in TTF. For example, TTF is halved if T increases from 25°C to 36°C or from 175°C to 200°C.

Although from Eq.(1), TTF is inversely proportional to the second power of average current density, the fact that the interconnect temperature T is a function of the current density makes the dependence on current density less apparent. Under DC conditions, the temperature T can be easily calculated from the current density and the thermal resistance of the structure. However, under pulse DC conditions, the problem of calculating T and TTF becomes difficult. The amount of self-heating under time-varying conditions is dependent on the frequency, duty factor as well as the structure geometry.

In this paper, we present our simulation results, an experimental technique and a model for estimating the temperature rise and time-to-failure of interconnect. We introduce the concept of derating factor for electromigration TTF due to self-heating. The derating factor is the factor the lifetime is reduced by temperature rise in the interconnect. Our results show that in the limit of high frequencies ($1/f \ll \tau_T$) the characteristic thermal time constant $\tau_T \sim 1\mu s$ the temperature rise can be estimated in a straightforward manner using the root-mean-square current density after the thermal resistance of the structure has been determined from DC measurements.

Discussion of Simulation and Experimental Results

Transient heat flow analysis using 2-dimensional finite element method [2] was used to calculate the temperature rise in Al-2%Si lines. The time-dependent solutions were found by the use of Green's function, i.e. the impulse response for a particular structure was first simulated and later convoluted with the power waveform to give the temperature distribution and the time-varying temperature data. We assume that the interconnect has sufficient length that it can be treated as semi-infinite, and only the temperature distribution of the cross section needs to be solved. Two examples of impulse response are shown in Fig.1 for 1.0 μm , 2.0 μm wide, 750Å thick Al-2%Si on 0.96 μm SiO₂. The substrate is pure Si. The thermal time constants from best fit are 0.36 μs and 0.39 μs respectively. The convolution approach reduces the amount of cpu time needed to generate a family of curves (each with different duty factor, frequency and power) for a particular device structure.

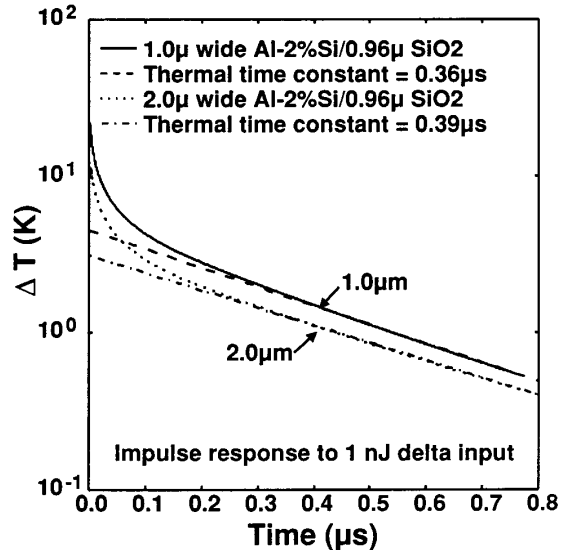


Fig.1. Impulse response from a 1nJ delta power input simulated by 2-dimensional transient heat flow analysis for 1.0 μm wide and 2.0 μm wide, 750Å thick Al-2%Si on 0.96 μm SiO₂ on Si wafer.

Snapshots of the heat flow simulation (taken at the end of current pulse after steady state is reached) for two interconnect structures are given in Fig.2 and Fig.3. The rectangular current pulse in the lines has a peak value of $2 \times 10^7 A/cm^2$ and the resistivity of the Al-2%Si used in computing the dissipated power is $4.5 \times 10^{-6} \Omega \cdot cm$. The waveform frequency is 200kHz and the duty factor is 0.75. The temperature of the Al-2%Si line is uniform owing to its large thermal conductivity. Most of the temperature gradient is found in the SiO₂ region. Using the simulated temperature rise results, we computed the derating factor for TTF at ambient temperature of 25°C (assuming $E_a = 0.5eV$ in Eq.(1)) by substituting the temperature at the middle of the pulse into Eq.(1). The results of our calculation for passivated and unpassivated interconnects are given in Table 1. One can see from Table 1 that self-heating is severe in all cases (74°C to 169°C), with the thicker oxide structure suffer the largest temperature rise and therefore the worst derating factor for TTF. The passivated structure has the the least self-heating among the three because of additional heat conduction path around the metal line. Apart from the dependence on oxide thickness and passivation, the interconnect temperature can be a function of other heat generating elements in the vicinity. This is illustrated in Fig.3 for a two-level metallization structure. Three 1 μm first-level metal lines (running into the page) with 1.0 μm separation and a wide 4.0 μm second-level metal line (running horizontally) all carry the same current waveform (200kHz 75% Duty Factor) and current density ($2 \times 10^7 A/cm^2$). The self-heating for all four interconnect in this structure is worst compared to the individual lines in

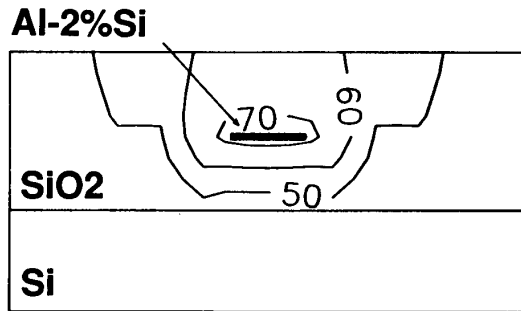


Fig.2. Temperature contour map from simulation for 1.0 μm wide 750 \AA thick Al-2%Si on 0.96 μm SiO₂ and 1.1 μm oxide passivation. The stress conditions was: 200kHz 0.75 duty factor, peak current density is $2 \times 10^7 \text{A/cm}^2$ and the ambient temperature is 25 $^\circ\text{C}$.

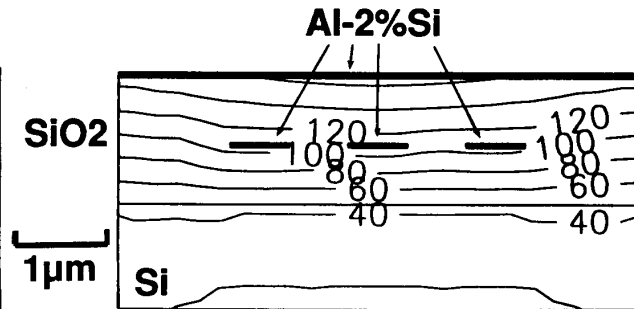


Fig.3. Temperature contour map for a two-level metallization structure. The three 1.0 μm wide 750 \AA thick Al-2%Si lines (running into the page) are buried in 2.1 μm SiO₂ underneath a 4.0 μm wide Al-2%Si (running horizontally across the page). All four lines are powered by 200kHz, 0.75 duty factor, $2 \times 10^7 \text{A/cm}^2$ pulse DC current. The ambient temperature is 25 $^\circ\text{C}$.

Structure	1 μ Al-2%Si on 2.1 SiO ₂ no passivation	1 μ Al-2%Si on 0.96 SiO ₂ no passivation	1 μ Al-2%Si on 0.96 SiO ₂ 1.1 oxide passivation	Center buried 1 μ Al-2%Si (Fig.3)	Top 4 μ Al-2%Si (Fig.3)
Temperature	107	84.3	73.8	113	169
Derating Factor	0.015	0.040	0.065	0.012	0.002

Table 1. Derating factor for TTF at 25 $^\circ\text{C}$ calculated from simulation for structures shown in Fig.2 and Fig.3. The frequency of the waveform is 200kHz, duty factor is 0.75 and current density is $2 \times 10^7 \text{A/cm}^2$. E_a in Eq.(1) is taken to be 0.5eV.

Tab.1: the temperatures of the wide line is higher compared to that of the Al line on 2.1 μm oxide, and temperatures of the buried line are likewise larger than that of the passivated Al line in Fig.2. We see in this example the reliability for interconnects in close proximity can be adversely affected. The environment and the structure of the metal lines have to be considered when making estimation for the derating factor for TTF.

Constant DC experiment was performed to obtain the thermal resistance values for a number of structures for comparison (see experimental data in Fig.4). We used in our calculation the power dissipated in the line, and therefore include the resistance increase in the Al-2%Si line due to self-heating. As expected from our simulation in Fig.2, the 1.0 μm line on 2.1 μm oxide has the largest thermal resistance (which is equal to the slope in Fig.4) and the passivated 2.0 μm line on 0.96 μm oxide has the lowest thermal resistance. We adjusted the value for the thermal conductivity of silicon oxide ($k_{ox} = 0.015 \text{Wcm}^{-1}\text{K}^{-1}$) in the simulation to give the best fit with the experimental thermal resistance. Simulations were then used to generate the thermal resistance \times length (equivalent to $\Delta T / \text{Power per length}$) versus interconnect width curves for four structures with different oxide thicknesses, passivated and unpassivated (Fig.4). The use of this unfamiliar quantity, thermal resistance \times length, is a direct result of our assumption that the interconnect is infinitely long in the length dimension, and that the temperature rise is independent of length. To illustrate this point and the use of this graph: the power per length dissipated in the interconnect is given by:

$$\frac{P}{L} = J^2 \rho A \quad (2)$$

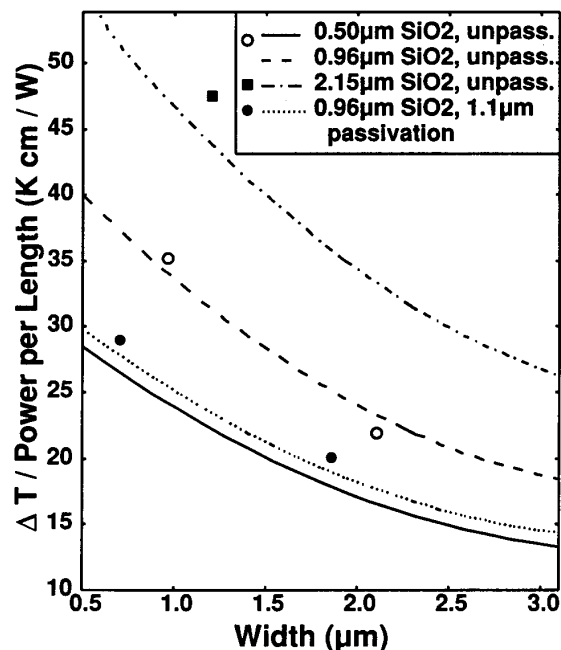


Fig.4. The thermal resistance simulated as a function of width for passivated and unpassivated Al interconnect. The quantity on the y-axis is thermal resistance \times length or ratio of temperature rise and power dissipated per length of the conductor. The symbols in the plot indicate experimental data

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where J (in A/cm^2) is the current density, ρ (in $\Omega \cdot cm$) is the resistivity of the metal and A (in cm^2) is the cross section of the interconnect. The temperature rise can then be calculated by multiplying power per length with the value read off from Fig.4 for a given width and oxide thickness.

The temperature of the Al-2%Si test stripe as a function of time under pulse DC conditions can be measured by using the set-up shown in Fig.5. The circuit which was used to generate the pulse DC current (which is omitted in Fig.5) can be found in Ref[1]. The digitizing scope was used to record the voltage and current of the four terminal test device. The temperature can then be calculated from the measured resistance. Prior to the measurement, the temperature coefficient of resistivity was determined by heating the wafer isothermally and measuring the resistance as a function of temperature. It has a value of $2.5 \times 10^{-3} K^{-1}$.

Figs.6(a) and 6(b) compare the experimental and simulated temperature excursions for $1\mu m$ wide, 750\AA thick Al-2%Si on $0.96\mu m$ SiO₂ powered by 75% duty factor rectangular pulses of 200kHz and 2.5MHz. The peak current density was $2 \times 10^7 A/cm^2$. The 200kHz data display large thermal excursion because the on-time and off-time of the pulse is much greater than the thermal time constant ($\tau_T = 0.36\mu s$ from simulation in Fig.1). Consequently, the temperature of the line approached the steady state constant DC powering level ($88.5^\circ C$ from Fig.4) in each pulse. Conversely, when the pulse period is comparable to the thermal time constant (τ_T) in the 2.5MHz experiment, and the data show smaller temperature excursion. The temperature is seen to vary $\pm 5^\circ C$ about $66^\circ C$, which is close to the value of $72.6^\circ C$ predicted from ΔT in Fig.4 by taking the average power of the current

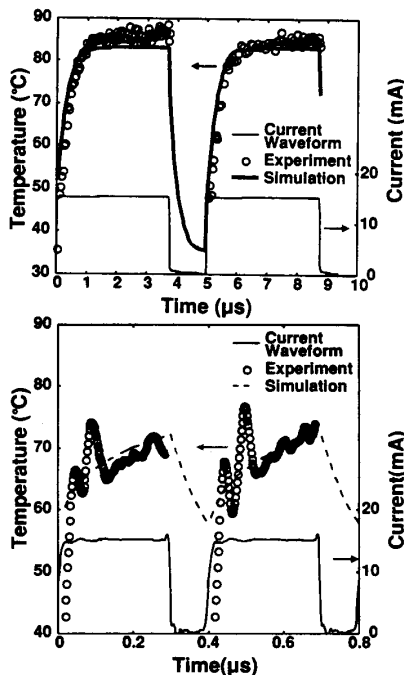


Fig.6. Experimental measurement and simulation results for the Al-2%Si line in the structure shown in Fig.2(b) under the conditions: (a) 200kHz 0.75 duty factor, (b) 2.5MHz 0.75 duty factor. The peak current density is $2 \times 10^7 A/cm^2$.

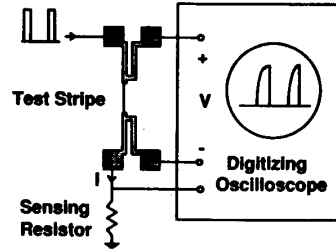


Fig.5. Experimental set-up for measuring transient temperature change in Al line.

waveform. This suggests that in the limit of high frequencies ($f \gg 1/\tau_T$), the interconnect "sees" an average power waveform. In this limit, the temperature as a function of time consists of a constant steady state value superposed with a small ripple and can be calculated using J_{rms} in Eq.(2).

Experimentally measured temperature excursions for 40kHz, 200kHz and 2.5MHz waveforms, all having peak current density $2 \times 10^7 A/cm^2$ are plotted as a function of duty factor in Fig.7. It can be seen again that both self-heating and temperature excursions are smaller for the 2.5MHz data. The 40kHz and 200kHz data for 50% and 75% duty factors are similar indicating that at these frequencies and duty factors, the metal line is essentially powered by a constant DC waveform during the on-time of the pulse. As a result the temperature is independent of frequencies and insensitive to duty factor (provided that the pulse-on time is much longer than τ_T). The derating factor for TTF (see Fig.8) can be found similarly by substituting the line temperature in Eq.(1). The calculated values are indicated by the symbols in Fig.8. The lines in Fig.8 are results from thermal simulation. In the high frequency regime (above 5MHz), the temperature in the line is determined by the root-mean-square current, i.e. the temperature is constant for a given duty factor regardless of frequency. As a result the derating factor is constant above 5MHz. As frequency is reduced, the temperature exhibits larger excursion as the period of the pulse becomes comparable to the thermal time constant ($0.36\mu s$). In this regime, the derating factor is a function of both the duty factor and frequency of the waveform. At lower frequency, the derating factor is independent of frequency and duty factor because the on-time of the pulse is large enough that DC steady state temperature is reached in the line, i.e. the temperature rise is determined by the peak current density of the pulse. In the limit of very low frequency, we would expect the derating factor to approach asymptotically the DC derating factor (calculated from data in Fig.4) regardless of duty factor.

The peak current density was kept constant in generating the data for Figs.7-8. However, average current density (J_{ave}) is usually quoted as a design rule for interconnect because TTF is inversely proportional to the power of J_{ave} , therefore it would be interesting to investigate the validity of J_{ave} design rule from the point of self-heating. This is given in Fig.9 where the calculated derating factor for TTF at ambient temperature of $25^\circ C$ is plotted against duty factor while keeping the average current density constant. In the DC limit, the self-heating in the interconnect at current densities 1×10^5 to $1 \times 10^6 A/cm^2$ is small. As a result, the Al temperature is essentially the ambient temperature $25^\circ C$ and no derating is necessary (the derating factor is unity). As the duty factor is decreased, the peak current density of the current waveform is increased to keep J_{ave} constant. The increased power dissipation associated with higher current density (higher J_{rms}) causes larger temperature rise due to self-heating. We observe that for duty factor greater than 0.1%,

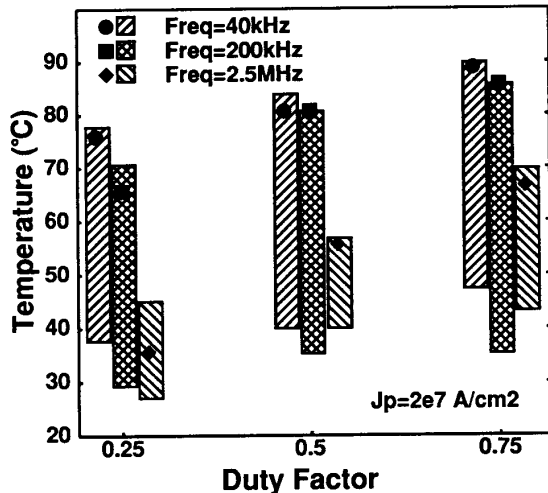


Fig.7. Temperature excursions measured in Al-2%Si line for the structure in Fig.2(b) as a function of duty factor for three frequencies. The peak current density is $2 \times 10^7 \text{ A/cm}^2$. The symbols denote the temperatures taken at the middle of the on-time pulse.

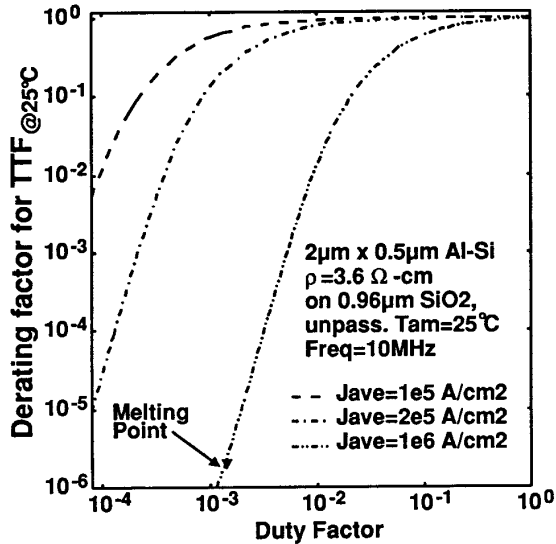


Fig.9. The derating factor for TTF at ambient temperature of 25°C from thermal simulation as a function of duty factor. The average current density was kept constant for each curve.

the electromigration lifetime of the interconnect ($2\mu\text{m} \times 0.5\mu\text{m}$ Al-Si on $1.0\mu\text{m}$ SiO_2) is degraded at most 10 times if the design rule of $J_{ave} = 2 \times 10^5 \text{ A/cm}^2$ is used. However if we were to increase the design rule to $J_{ave} = 1 \times 10^6 \text{ A/cm}^2$, the reliability would become unacceptable (in fact, the metal reaches melting point at $\sim 0.1\%$ duty factor with the peak current at 10 A).

Summary

The self-heating effect in Al interconnect was experimentally measured and simulated using the technique out-

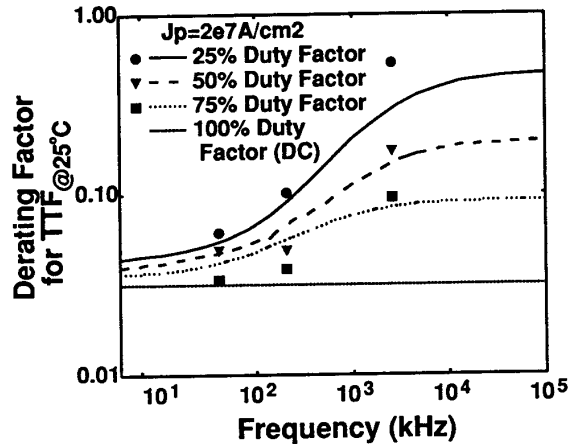


Fig.8. The derating factor for TTF at ambient temperature of 25°C calculated by substituting the temperature at the middle of the pulse in Fig.7 to Eq.(1). The value of 1.0 represents no derating of TTF. The peak current density is the same: $2 \times 10^7 \text{ A/cm}^2$ for all the data. The lines represent simulation results.

lined above. The importance of self-heating in interconnect reliability depends on the geometry of the interconnect, the oxide thickness, passivation and the current density as well as the duty factor and frequency of the current waveforms. For practical operating frequency ($> 10\text{MHz}$) as in CMOS integrated circuits, the on-time of the pulse and the period are much smaller than the thermal response time of the interconnect. Thus, the temperature rise can be estimated from the average power dissipated in the metal, i.e. it is proportional to the second power of the root-mean-square current density. The implication of the temperature dependence on J_{rms} on the usually quoted J_{ave} design rule was examined. It was deduced from our experimental and simulation data that self-heating is probably not significant for the usual design rule average current density of $1 \times 10^5 \text{ A/cm}^2$ for operation at frequency $> 10\text{MHz}$ and duty factor $> 0.1\%$. However, if the design rule is increased to $1 \times 10^6 \text{ A/cm}^2$, self-heating might become significant.

Under high current density (J_p in excess of $1 \times 10^7 \text{ A/cm}^2$) such as in accelerated lifetime experiments, thermal cycling and its effect on the experimental TTF may have to be considered. The technique presented here is a convenient way to evaluate self-heating effects on TTF for a given structure geometry and current waveform.

Acknowledgement

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Reference

- [1] B. K. Liew, N. W. Cheung, and C. Hu, "Electromigration interconnect lifetime under AC and pulse DC stress," *Proc. 29th Annual Reliability Physics Symp. IEEE*, p. 215, 1989.
- [2] B. K. Liew, N. W. Cheung, and C. Hu, "Effects of high current pulses on integrated circuit metallization reliability," *Proc. Intersociety Conference on Thermal Phenomena in the Fabrication and Operation of Electronic Components*, p. 1, 1988.