Reliability Degradation with Electrical, Thermal and Thermal Gradient Stress in Interconnects

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***Abstract*—An empirical reliability model for electromigration-induced failure in metal interconnects under thermal, electrical, and thermal gradient stress is introduced. Based upon the limited reported measurements on static thermal gradient stress that are available, this model incorporates thermal gradient stress into the probability density function of the time to failure, t_F. With this model, temperature measurement accuracy and temperature gradient measurement accuracy requirements for multi-site on-chip sensors that can be used in power/thermal management algorithms are developed that target achieving 10% accuracy in the median time to failure (MTF) of a circuit.**

Key words: reliability, electromigration, interconnects, failure mechanisms, thermal gradient.

I. INTRODUCTION

Electromigration (EM) in integrated circuit metallization is a major contributor to reliability degradation in today's microelectronics industry. Pressure on designers to minimize interconnect area and capacitance result in high current densities that are limited by reliability implications. Paralleling the pressure for high current densities are demands for high speed which causes the operating temperature to raise both locally and globally[1]. High current densities result in drift of the metal atoms that comprise interconnects. This mass transport is caused by momentum transfer between conducting electrons and metal atoms. It is well known that this metal atom drift is a highly nonlinear function of both current density and temperature. This drift in metal atoms is termed electromigration. Electromigration will probabilistically result in failure of interconnects within the useful life of an integrated circuit if the drift rate is too large. Local power dissipation variations, in part attributable to joule heating, produce thermal gradients. Thermal gradients cause degradation in interconnects through thermomigration (TM). Although, the magnitude of TM flux is much smaller than EM flux, thermal gradients in the presence of high current densities significantly degrade the reliability of interconnects [1],[2]. In this paper we will use the term electromigration to denote the degradation in metal interconnects irrespective of whether the physical mechanisms involved are electromigration, thermomigration, or some combination of the two. Though many authors express concern about the effects of thermal gradients on the reliability of interconnects, there are limited research results in the literature that focus on the effects of thermal gradients on electromigration.

The seminal work of Black, in 1967 [3] and 1969 [4], is widely used to characterize the relationship between the reliability and constant electrical and thermal stress. Black presented a model for the Median Time to Failure (MTF) of interconnects in the presence of electrical and thermal stress. Although Black does not discuss the underlying Probability Density Function (PDF) from which the MTF is derived, Lognormal and/or Weibull distributions often provide good correlation with measured failure data. In this work, an empirical statistical model will be introduced that attempts to combine the effects of electrical stress, thermal stress, and thermal gradient stress (ETTG) on the reliability of interconnects. The purpose of this model is to obtain an estimate of the level of degradation in reliability that will occur in the presence of significant levels of combined ETTG stress and to obtain an estimate of the accuracy needed for on-chip temperature and temperature gradient sensors if they are used as part of a power/thermal management algorithm to manage the reliability of an integrated circuit.

II. RELIABILITY MODELING

Electromigration is a statistical process and causes wear out in metal interconnects. The time to failure due to electromigration, t_F, is a random variable that characterizes the failure of an interconnect. Corresponding to the random variable t_F are the PDF $f(t_F)$, the Cumulative Distribution Function (CDF) $F(t_F)$, and the Reliability Function $R(t_F)$. They are related by the expressions,

$$F(t_F) = \int_{t=0}^{t_F} f(\tau)\,d\tau \tag{1}$$

$$R(t_F) = 1 - F(t_F) \tag{2}$$

The MTF is defined as

$$0.5 = \int_{t_F=0}^{MTF} f(t_F)\,dt_F = F^{-1}(0.5) \tag{3}$$

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III. ELECTRICAL/THERMAL/THERMAL GRADIENT STRESS

Black's empirical expression for MTF due to electromigration [3] is well established and can be expressed as

$$\mathrm{MTF} = \begin{cases} \infty & J < J_{CRIT} \\ A_0 \left(J - J_{CRIT}\right)^{-N} e^{(E_a/kT)} & J > J_{CRIT} \end{cases} \quad (4)$$

where T is absolute temperature in K, J is the current density, and k is Boltzman's constant. In this expression, the stress parameters, J and T, are assumed to be constant. The parameters A_0, J_{CRIT}, N, and E_a are constants dependent upon properties of the materials. Geometry information is included in the constant A_0. J_{CRIT} is the critical current density and is around as 1 MA/ cm^2 for aluminum [5]. The constant N is typically between 1 and 3. For aluminum and copper interconnects N=2 [5] is often used. E_a is the activation energy. For aluminum interconnects E_a typically ranges between 0.7eV and 0.9eV.

Though static thermal gradient stress is known to limit lifetime of an interconnect, there is little in the literature to suggest how this should be incorporated into a reliability model that jointly includes the effects of current stress, thermal stress, and thermal gradient stress. Lacking such a model, we have empirically included the thermal gradient as a stress parameter along with temperature and current density by modifying the MTF equation of Black equation (5) as a separable function of J, T, and the thermal gradient ΔT as,

$$\mathrm{MTF} = \begin{cases} \infty & J < J_{CRIT} \\ A_0 \left(J - J_{CRIT}\right)^{-N} e^{(E_a/kT)} \left(1 + a_1 \Delta T + a_2 \Delta T^2\right) & J > J_{CRIT} \end{cases} \quad (5)$$

The parameters in the polynomial equation are obtained by fitting experimental MTF measurements [1] to actual temperature gradients.

It will be assumed that the CDF can be expressed using the lognormal distribution as [6]

$$F_{LNi}\left(t_F, \mu_i, \sigma\right) = F_{N01}\left(\frac{\ln\left(t_F\right) - \mu_i}{\sigma}\right) \quad (6)$$

where

$$\mu_i = \ln\left(\left(A_0 \left(J_i - J_{CRIT}\right)^{-N} e^{(E_a/kT_i)}\right)\left(1 + a_1 \Delta T + a_2 \Delta T^2\right)\right) \quad (7)$$

and where F_{N01} denotes the CDF of the Normal (0,1) random variable. The parameter σ determines the steepness of the CDF in the region around $t_F = F^{-1}(0.5)$ and ln(x) is the natural logarithm function.

Existing power/thermal management algorithms typically throttle the speed of operation when the temperature reaches a predetermined trigger level and this level is often based upon the assumption that the current density stress is maintained at some maximum nominal level, J_{NOM}. By throttling the speed, the temperature can ideally be maintained at or below the trigger temperature, denoted as T_{NOM}. The trigger temperature is typically established so that if the device is operated continuously at T_{NOM} and the current is maintained continuously at J_{NOM} the circuit will meet a target MTF. Some power/thermal management algorithms have a single temperature sensor and some use multiple on-chip temperature sensors. In the latter case, the power/thermal management algorithm will ideally keep the temperature at each sensor location at or below T_{NOM}.

With existing approaches to power/thermal management, thermal gradient information is not a part of reported speed throttling processes and if large temperature gradients are present, the temperature-based throttling will not be adequate for meeting target MTF goals. If on-chip temperature gradient sensors are strategically placed on a die at locations where thermal gradients are likely to be most critical, the power/thermal management algorithm can be modified to also throttle speed whenever the thermal gradients meet a trigger gradient value. This trigger gradient is denoted as ΔT_{NOM}. The analogous power/thermal management strategy would be to pick both T_{NOM} and ΔT_{NOM} so that if the device is operated continuously at the ETTG stress level of J_{NOM}, T_{NOM}, and ΔT_{NOM}, then the circuit will meet a target MTF goal. To implement such an algorithm, a model of the MTF that incorporates the ETTG stress conditions is needed as well as both temperature and temperature gradient sensors. Lacking an established model, we will use the empirical model of (5) which incorporates the ETTG stress parameters. Since the MTF is quite sensitive to small changes in stress conditions, it is also necessary to determine the accuracy requirements for both the temperature sensors and the temperature gradient sensors. We will now obtain an estimate of the thermal gradient stress parameters, a_1 and a_2 in (5).

In [1], Nguyen et. el. studied the effects of thermal gradients on an AlSi(1%)Cu(.04%) interconnect with an accelerated lifetime test. In their study, the temperature at the hot side of the interconnect was maintained at 202^0C and the temperature at the low side was adjusted in four separate tests to create thermal gradients of 0, 0.09, 0.19, and 0.28^0C/μm. In these tests, the MTF decreased from 46.6h when there was no gradient to 41.8h, 19.8h, and 4.3h respectively with the larger thermal gradients. With these measurements and the assumption that the MTF is a separable function of J, T, and the gradient ΔT, the second-order polynomial fit parameters a_1 and a_2 of (5) can be estimated. An estimate of these parameters is a_1=-2.629 and a_2=-2.088.

We will now use these fit parameters to predict the MTF under different ETTG conditions in a state of the art process. Since it is recognized that the metal characteristics may be somewhat different and the assumption of a separable function for the MTF is strictly empirical, there will be some model errors but lacking experimental data for predicting the effects of thermal gradients, the results obtained should at least be indicative of what could happen in these processes when thermal gradients are present. Typical values for stress variables J_{NOM} and T_{NOM} for the 0.45 nm technology node are 3 MA/cm^2 [7] and 110 ^{0}C [8] respectively. Using these stress variables, and assuming a lognormal distribution with shape factor of σ=0.3, with typical values for A_0 and E_a in (5), we obtain the CDF plots shown in Fig. 1 under the four gradient conditions 0, 0.09, 0.19, and 0.28^0C/μm. The corresponding MTF for the four gradient conditions are summarized in Table 1.

Table I. MTF in Different ΔT with normal Stress

Current Density (J) 3 MA/cm^2	**(under Temp Gradient (ΔT) ^{0}C/μm**	**μ**	**MTF (years)**
Temperature (T) 110 ^{0}C	0	2.76	15.8
	0.09	2.47	11.8
	0.19	1.91	6.8
	0.28	0.46	1.6

From these results it is observed that under a constant ambient temperature and current density condition, when the thermal gradient is increased from 0^{0}C/μm to 0.28^{0}C/μm, the MTF has decreased by factor of approximately 10. As expected, this is the same relative decrease that was reported in [1].

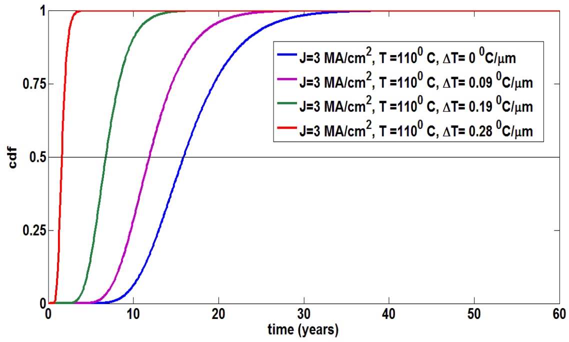

Figure 1: CDF plots under different ΔT in T_{NOM} and J_{NOM} conditions

A comparison will now be made with the degradation in reliability due to thermal gradients with changes in reliability due to changes in electrical or temperature stress. In [9], the effects of changes in electrical and thermal stress were considered using the distribution function that differed from that used here with the exception that temperature gradient effects were ignored (i.e. with a_1=a_2=0). These results are repeated in Fig. 2 and the results are compared numerically in Table II. Comparing the results in Table I and Table II, it can be seen that a gradient of 0.09 ^{0}C/μm will cause about the same decrease in reliability as an increase of temperature of 6^{0}C in the absence of thermal gradients.

Table II. MTF in Different Stress in absence of ΔT

Current Density (J) (MA/cm^2)	**Temperature (T) ^{0}C**	**μ**	**MTF (years)**
3.3(J+10%J)	110^{0}C+6^{0}C	2.09	8.2
3	110^{0}C+6^{0}C	2.37	10.8
3	110^{0}C	2.76	16
3	110^{0}C-6^{0}C	3.17	23.8
2.7 (J-10%J)	110^{0}C-6^{0}C	3.50	33

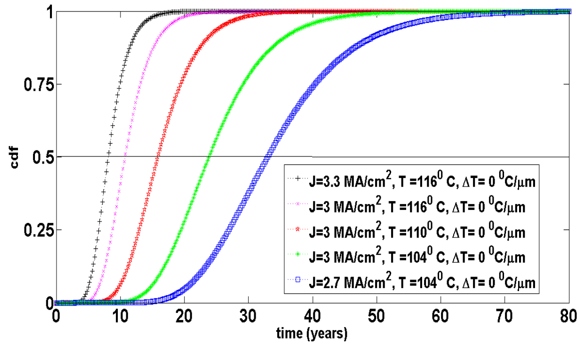

Figure 2: CDF plots under different T and J in absence of ΔT

Fig.3, Fig.4, and Fig.5 compare the reliability under various combinations of the ETTG stress parameters. The results from these plots are summarized in Table III, Table IV, and Table V.

Table III. MTF in Different Stress when ΔT=0.09^0 C/μm

Current Density (J) (MA/cm^2)	**Temperature (T)**	**μ**	**MTF (years)**
3.3(J+10%J)	110^{0}C+6^{0}C	1.80	6
3	110^{0}C+6^{0}C	2.08	18
3	110^{0}C	2.47	11.8
3	110^{0}C-6^{0}C	2.87	17.8
2.7 (J-10%J)	110^{0}C-6^{0}C	3.20	24.6

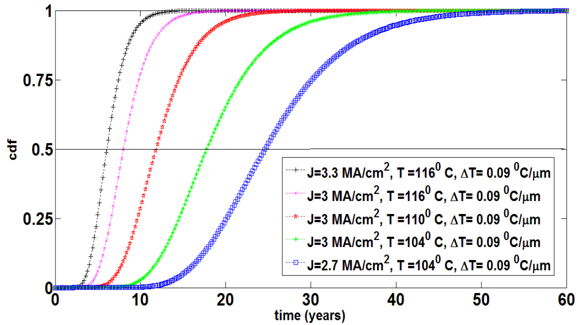

Figure 3: CDF plots under different T, J when ΔT = 0.09^0 C/μm

Table IV. MTF in Different Stress when ΔT=0.19^0 C/μm

Current Density (J) (MA/cm^2)	**Temperature (T) ^{0}C**	**μ**	**MTF (years)**
3.3(J+10%J)	110^{0}C+6^{0}C	1.24	3.4
3	110^{0}C+6^{0}C	1.52	4.6
3	110^{0}C	1.91	6.8
3	110^{0}C-6^{0}C	2.32	10
2.7 (J-10%J)	110^{0}C-6^{0}C	2.64	14

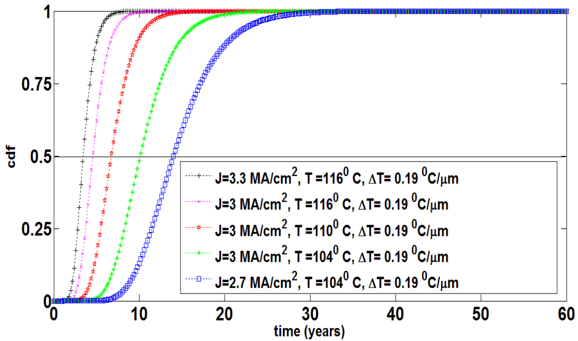

Figure 4: CDF plots under different T,J when ΔT = 0.19^0 C/μm

Table V. MTF in Different Stress when ΔT=0.28^0 C/μm

Current Density (J) (MA/cm^2)	**Temperature (T)**	**μ**	**MTF (years)**
3.3(J+10%J)	110^{0}C+6^{0}C	-0.21	0.82
3	110^{0}C+6^{0}C	0.07	1.08
3	110^{0}C	0.46	1.6
3	110^{0}C-6^{0}C	0.87	2.38
2.7 (J-10%J)	110^{0}C-6^{0}C	1.19	3.32

From these simulation results, it can be observed that the MTF decreased from 33 years in the minimum stress condition of J=2.7MA/cm^2, T=104^{0}C, ΔT=0^{0}C/μm to 0.82

years in the maximum stress condition J=3.3MA/cm^2, T=116^{0}C, ΔT=0.28^{0}C/μm. This change in stress conditions is rather modest yet the change in reliability as characterized by the MTF is a factor of approximately 40. More importantly, it can be seen that each of the ETTG stress factors contribute significantly to the degradation in reliability.

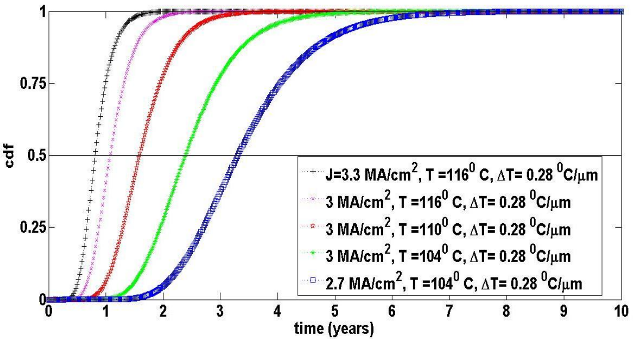

Figure 5: CDF plots under different T,J when ΔT = 0.28^0 C/μm

The question naturally arises; How large of thermal gradient stresses are likely to occur? Though not quantized, thermal gradient stress in the 0.05^{0}C/μm has been reported in several papers focusing on hot spots. Other work, including that in [1] considers larger gradients. Lloyd [10] recently suggested thermal gradients well in excess of 1^{0}C/μm "will be found". Much of the reported thermal gradient information has focused on single-core processors. With multi-core processors now common, with increases in the number of cores, and with projections for increasing the total power dissipation on processors by a factor of 4 in the next few years while maintaining approximately the same die area, much larger thermal gradients can be expected and these thermal gradients will likely play increasingly important roles in the reliability of interconnects.

IV. ACCURACY REQUIREMENTS FOR TEMPERATURE AND TEMPERATURE GRADIENT SENSORS

If power/thermal management algorithms use measured temperature and in the future, measured temperature gradient information to throttle operating frequency for the purpose of meeting reliability targets, the question naturally arises about how accurately these measurements need to be made.

It was recently shown [9] that to maintain the MTF to within ±10% of the target MTF, the temperature must be measured to within ±1.6^{0}C. This requirement was established under the assumption that thermal gradients are not contributing to degraded lifetime. Using the lognormal model discussed above, it can be shown that if there are no errors in temperature measurement, and if a trigger thermal gradient of 0.2^0 C/μm is established, then the accuracy of the thermal gradient sensor must be 0.011^{0}C/μm. If the temperature gradient is measured by taking the difference of two temperatures that are 10 μm apart, the temperature difference must be accurate to 0.11^{0}C to maintain ±10% accuracy in the MTF. Practically, some of the measurement error budget should be allocated to the temperature sensor and some to the temperature gradient sensor. Therefore, to maintain the ±10% accuracy in the MTF, if the temperature accuracy is increased to ±1.2^{0}C, the temperature gradient measurement could be reduced to 0.003^{0}C/μm and the corresponding temperature difference accuracy to 0.03^{0}C.

At this stage, whether it is ultimately practical to maintain accuracy of a target MTF that is within ±10% of the target MTF is not clear. Unless some major breakthrough occurs in the design of temperature sensors, a single point temperature calibration during production testing will be necessary. The overall accuracy of the calibrated temperature sensor will be the sum of the accuracy of the calibration temperature and the accuracy of the temperature sensor itself. In existing production test flows, it is difficult to measure the calibration temperature at a sensor point on the silicon wafer to much better than ±1^{0}C. This places a lower bound on the accuracy of the temperature sensor. So, if the temperature sensor accuracy requirement is ±1.2^{0}C, the accuracy of the temperature sensor circuit itself must be at the ±0.2^{0}C level which is achievable. Since the gradient sensor is dependent upon a temperature difference rather than an absolute temperature, reasonable performance of a temperature gradient sensor may be achievable without calibration.

V. CONCLUSION

A significant reduction in the MTF due to thermal gradients is a major contributing factor to reliability degradation in interconnects in some circuits today and the problem is likely to get much worse as power density increases in next-generation systems. By incorporating the output of a number of strategically placed thermal and thermal gradient sensors in the power/thermal management algorithm, significant improvements in reliability can be achieved while still meeting target reliability goals. Good accuracy on the temperature sensors and the temperature gradient sensors is needed if tight MTF goals are to be met.

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