Reliability Modeling of Metal Interconnects with Time-Dependent Electrical and Thermal Stress

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***Abstract*— A reliability model for electromigration-induced failure in metal interconnects under time-dependent stress is introduced. In contrast to existing reliability models that are based upon the assumption that stress is constant throughout the useful life of a system, this model includes provisions for the more realistic situation where both thermal stress and current stress are time-dependent. A single parameter which can be represented as a real number is used to incorporate the total effects of the stress history making this approach applicable for dynamic power/thermal management algorithms.**

Key words: reliability, electromigration, interconnects, failure mechanisms

I. INTRODUCTION

Advancements in the microelectronics industry parallel [1] the area miniaturization of devices and interconnects in integrated circuits. As the dimensions of the interconnects are reduced, the current density is increased. Reliability of interconnects is a major concern in the semiconductor industry. Electromigration is a primary cause of the failure of interconnects due to the formation of hillocks or creation of voids in the presence of thermal or electrical stress. Many papers have been written on modeling electromigration in interconnects in integrated circuits since the seminal work of Black in 1967 [1] and 1969 [2]. The useful life of an integrated circuit depends strongly upon the level of stress that is applied throughout operating period or the device. This stress is usually time and temperature dependent.

The mean time to failure (MTTF) or the median time to failure (MTF) are often used as metrics to characterize the reliability of an interconnect. Though the intended useful life of a component is often considerably less than the MTTF or MTF, these metrics are widely used characterize reliability. Although most reliability assessments of electronic components are based upon an assumption of constant stress throughout the operating life of a component, stress is invariably highly time-dependent and this time dependence should be included if accurate reliability results are to be obtained.

Accelerated-stress lifetime testing is widely used for experimentally measuring reliability in the semiconductor industry. In most of the experiments, accelerated life testing is based on constant stress. Correspondingly, accelerated lifetime testing results are widely used to predict lifetime, e.g. MTF, under a “normal” operating stress which is invariably assumed to be time independent. Unfortunately, the actual stress is seldom time invariant. Because of the highly nonlinear relationship between lifetime and stress, the assumption of time-invariant stress introduces large errors in lifetime predictions. As a consequence, systems are often over-designed to assure acceptable reliability when the stress is time dependent or target reliability goals are not met when stress actually is nearly constant at an upper-stress bound.

In most previous work, modeling of electromigration focuses on a statistic such as MTF rather than the Probability Density Function (PDF) of the failure time. And even when the PDF is considered, there is not agreement amongst researchers about what PDF should be used to model the lifetime or how system parameters affect the functional form of the pdf. This lack of agreement is due, in part, to differences in the physical characteristics of the interconnects themselves associated with differences in grain sizes and interconnect geometries. In this work, we have developed a real-time wear model where the remaining life of a device can be predicted based upon the time-dependent thermal and electrical stress profile of the device.

II. RELIABILITY MODELING AND STRESS MODELING

In Black’s work [1], [2], a single analytical expression for the Mean Time to Failure and the Median Time to Failure, both denoted as MTF, was introduced. Black did not appear to distinguish between these two statistics. The distinction between these metrics is often not clear in the follow-on literature either and some authors’ use the term time-to-failure, TF, as another statistic to presumably characterize the same effects. To avoid possible confusion in this paper, the abbreviations MTTF will be used to denote Mean Time to

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Failure and MTF to denote Median Time to Failure. MTF and MTTF are both statistics of the lifetime of an interconnect which is a random variable characterized by a Probability Density Function $f(t_F)$ where t_F denotes the failure time. The failure time t_F denotes the actual failure time of a device and is a random variable. Corresponding to any Probability Density Function is the Cumulative Density Function (CDF) , $F(t_F)$, defined by

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

$F(t_F)$ is a monotone nondecreasing function of t_F that equals 0 at time $t_F=0$ and converges to 1 as $t_F \to \infty$.

Some authors prefer to work with the Reliability Function $R(t_F)$ (alternatively termed the Survival Function) that is defined as

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

The reliability function is a monotone decreasing function of t_F that equals 1 at time $t_F=0$ and converges to 0 as $t_F \to \infty$. In this work we concentrate on $F(t_F)$ though trivially the $R(t_F)$ results can be obtained from (2). The MTTF statistic is given by the expression

$$MTTF = \int_{t_F=0}^{\infty} t_F f(t_F)\, dt_F \tag{3}$$

and the MTF statistic by the implicit expression

$$0.5 = \int_{t_F=0}^{MTF} f(t_F)\, dt_F$$

or equivalently by the explicit expression

$$MTF = F^{-1}(0.5) \tag{4}$$

III. DIFFERENT STRESS CONDITION

Black's empirical expression for MTF due to electromigration [1] is well established and can be expressed as

$$MTF = \begin{cases} \infty & J < J_{CRIT} \\ A_0 (J-J_{CRIT})^{-N} e^{(E_a/kT)} & J > J_{CRIT} \end{cases} \tag{5}$$

where T is absolute temperature in K, J is the current density, and k is Boltzman's constant. All parameters in this expression are time-independent. In this expression, there are four process/material dependent model parameters, A_0, J_{CRIT}, N, and E_a. A_0 is a material property and geometry dependent constant. J_{CRIT} is the critical current density. J_{CRIT} is around as 1 MA/ cm^2 for aluminum [3]. N is a constant. The typically range of N is between 1 and 3. For aluminum and copper interconnects N=2 [3] is often used. E_a is the activation energy. For aluminum interconnects E_a typically ranges between 0.7eV and 0.9eV.

In this paper, a model is developed for the MTF when the electrical and thermal stresses are time variant. For notational convenience, it is assumed that these stresses are piecewise constant and that a sequence of time points, denoted as $\langle t_i \rangle_{i=0}^{m}$, denote times where the stress changes when $m \geq 1$. The time t_0 =0 denotes the "birth" time of the interconnect, that is, the time that a stress is first applied. If the stress remains constant throughout the use of the interconnect, then m=0 and existing models can be used to predict the MTF. When m>0, there are one or more changes in stress. The change in stress at any time point could correspond to a change in J, a change in T, or a change in both J and T. The stress vector ST is defined as

$$ST(t) = \begin{bmatrix} J_0(t) & T_0(t) \\ J_1(t) & T_1(t) \\ \cdots & \\ J_m(t) & T_m(t) \end{bmatrix} \tag{6}$$

where

$$\begin{aligned} J_i(t) &= J_i \quad \text{for} \quad t_i \le t < t_{i+1} \quad \forall\, 0 \le i \le m \\ T_i(t) &= T_i \quad \text{for} \quad t_i \le t < t_{i+1} \quad \forall\, 0 \le i \le m \end{aligned} \tag{7}$$

and where it is assumed that $t_{m+1} = \infty$ and $J_i > J_{CRIT} \quad \forall\, i$. These latter two assumptions are made strictly for notational convenience and neither is necessary. It is assumed that the amount of wear in the interconnect can be characterized by the time-dependent CDF, specifically, $F(t_F)$. Since the MTF satisfies the relationship

$$MTF = F^{-1}(0.5), \tag{8}$$

the MTF is determined from the CDF. It is further assumed that the same functional form of the CDF characterizes the failure time in each interval and that in the i^{th} interval, the stress is completely represented by a single "parameter" in that CDF and this "parameter" is the function $A_0 (J_i-J_{CRIT})^{-N} e^{(E_a/kT_i)}$ where J_i, A_0, J_{CRIT}, N, and T_i are constant throughout the i^{th} interval.

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

$$F_{LNi}(t_F, \mu_i, \sigma) = F_{N01}\left(\frac{\ln(t_F) - \mu_i}{\sigma} \right) \tag{9}$$

where $$\mu_i = \ln\left(A_0 (J_i-J_{CRIT})^{-N} e^{(E_a/kT_i)} \right) \tag{10}$$

and where F_{N01} denotes the CDF of the Normal (0,1) random variable. The parameter σ is a shape parameter of the distribution and ln(x) is the natural logarithm function. It is assumed that if the stress is constant throughout the life of the interconnect, the CDF satisfies the relationship

$$\text{If} \quad MTF_a > MTF_B \quad \text{then} \quad F_b(t_F) \ge F_a(t_F) \quad \forall\, t_F \ge 0 \tag{11}$$

Circuits are often designed to have an acceptable MTF under constant maximum stress at a given current density denoted as J_{MAX} and a given temperature denoted as T_{MAX}. Typical values for J_{MAX} and T_{MAX} for the 0.45 nm technology node are 3 MA/cm^2 [4] and 110 ^{0}C [5]. These stress conditions are often interpreted as guard bands and power/thermal management algorithms are often established to guarantee that these guard band values are not exceeded with the obvious assumption that if operation is maintained constant at the guard band limit, an acceptable MTF will be obtained.

CDF plots for five different constant stress conditions close to J_{MAX} and T_{MAX} based upon the lognormal distribution of (9) with shape factor σ=0.1 are shown in Fig. 1. The stress conditions are listed in Table 1 along with the corresponding MTF.

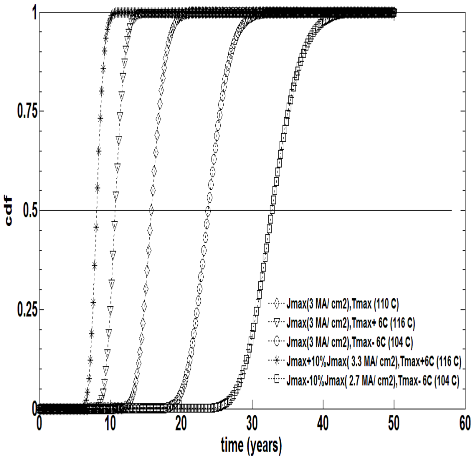

Figure 1: CDF plots under constant stress

TABLE I. MTF IN DIFFERENT CONSTANT STRESS

Current Density (J) (MA/cm^2)	**Temperature**	**µ**	**MTF (years)**
3.3(J+10%J)	110^0C+6^0C	2.09	8.1
3	110^0C+6^0C	2.37	10.7
3	110^0C	2.76	15.96
3	110^0C-6^0C	3.17	23.8
2.7 (J-10%J)	110^0C-6^0C	3.50	33

The high sensitivity of the MTF to stress is apparent from these plots. It can be observed that a 10% increment in current density and 6^0C temperature increment causes a 50% reduction in MTF. Even if current stress is unchanged, a 6^0C increment in temperature reduces the MTF by 32%.

Assuming a device has to maintain its MTF as ±10% of its nominal MTF. In that case, from the result it can be observed that the temperature should be measured accurately as $\pm 1.6^0C$. In the above stated condition, if current density also changes ±5% of nominal current density then temperature should be measured accurately as $\pm 0.5^0C$. Therefore, to measure reliability accurately, it is very crucial to keep track of stress profile very precisely.

IV. TIME DEPENDENT STRESS MODELING

It is assumed that in any stress interval, the CDF is equal to that which would be in effect had the same stress been applied at the translated time needed to maintain continuity of the CDF at the transition from the previous interval. This latter assumption is critical in what follows and can be interpreted as assuming that the amount of wear is characterized by the CDF. This wear stress assumption can be expressed mathematically as

$$F\left(t_F\right)=F_k\left(t_F\right) \qquad \text{for} \qquad t_k< t_F \leq t_{k+1} \qquad 0 \leq k \leq m \tag{12}$$

where for all $0 \leq k \leq m$,

$$F_k\left(t_F\right)=F_{k0}\left(t_F-t_k+F_{k0}^{-1}\left(F_{k-1}\left(t_k\right)\right)\right) \qquad \text{for} \qquad t_k< t_F \leq t_{k+1} \tag{13}$$

where $F_k\left(t_F\right)$ is the CDF in the interval $t_k < t_F \leq t_{k+1}$ and where $F_{k0}\left(t_F\right)$ is the CDF that corresponds to a constant stress of J_k and T_k throughout the life of the interconnect. From this expression, it can be observed that the effects of the entire stress history in any interval $t_k<t_F<t_{k+1}$ is dependent only upon the function $F_{k-1}(t_k)$ and thus only a single real number needs to be stored to predict the reliability at any point in time. This number needs to be updated each time a transition is made to a different interval. It can also be observed that the sequence $\left\langle F_{k-1}\left(t_k\right)\right\rangle_{k=1}^{\infty}$ is monotone and increasing with k. using equation (13) to model the time-dependent stress, four different time-dependent stress simulations were made. Simulation results are shown in Fig. 2- Fig. 4. Results are summarized in Table 2. In all cases, there were 11 different stress intervals which correspond to 10 stress transition times and two different stress levels, one termed the high stress and the other termed low stress. All time-dependent stress tests started with the low stress condition and then toggled between the high stress and low stress levels at each stress transition time. The high stress condition corresponds to $J=J_{MAX}$ and $T=T_{MAX}$ as identified above. The low stress condition corresponded to $J=0.85J_{MAX}$ and $T=T_{MAX}-10^oC$. These low stress conditions are still likely much higher than what would be experienced in many applications. Included in these four figures for comparison purposes are the CDF for constant high stress and constant low stress.

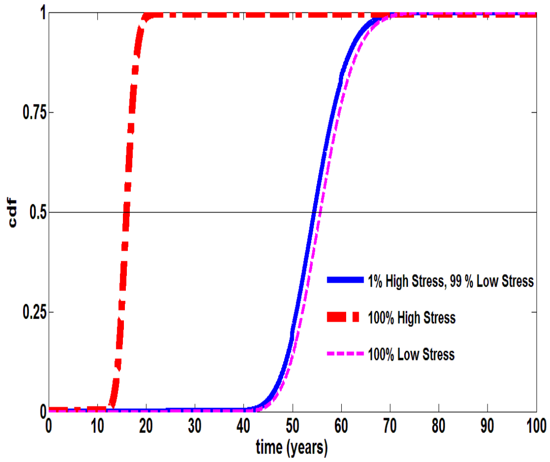

Figure 2: cdf vs time when high stress with 1% duty cycle (DC) and low stress with 99 % DC

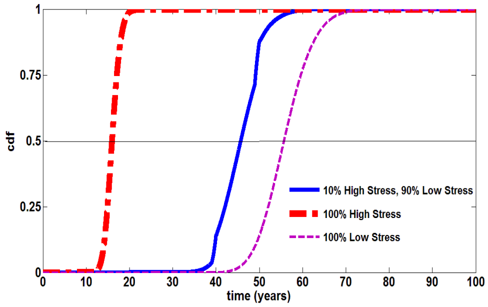

Figure 3: cdf vs time when high stress with 10% DC and low stress with 90 % DC

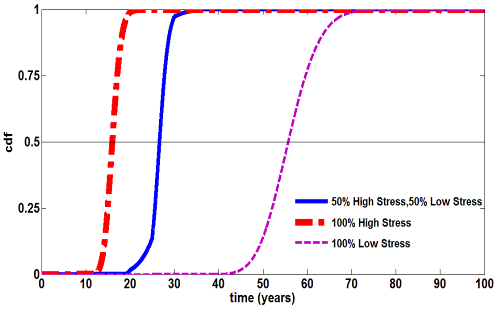

Figure 4: cdf vs time when high stress with 50% DC and low stress with 50 % DC

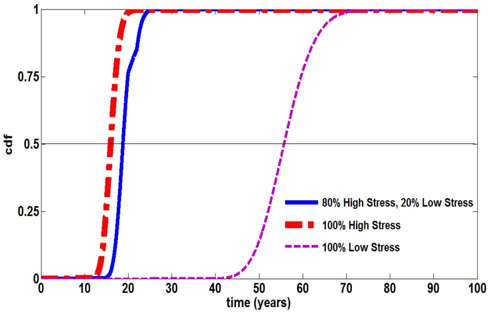

Figure 5: cdf vs time when high stress with 80% DC and low stress with 20 % DC

TABLE II. DIFFERENT MTF IN TIME VARIANT STRESS

High Stress	**Low Stress**	
Current Density (J_{max}), 3 MA/ cm^2,	Current Density (85%J_{max}) 2.55 MA/cm^2,	
Temperature (T_{max}) 110 ^{0}C	Temperature (,91% T_{max}) 110 ^{0}C-10^{0}C	
μ (High stress) (2.77)	μ(Low stress) (4.02)	MTF (years)
0% DC	100% DC	55.68
1% DC	99% DC	54.46
10% DC	90% DC	45.75
50% DC	50% DC	26.68
80% DC	20% DC	18.84
100% DC	0% DC	15.96

In the results shown in Fig. 2, there was a 1% high stress and a 99% low stress with the first stress transition occurring at 9.9 years the second occurring at 10.0 years and with the high and low stress intervals remaining constant through the remaining stress transitions. The MTF under the constant high stress and constant low stress range between 15.96 years and 55.68 years with the 1% time varying high stress corresponding to a MTF of 54.46 years. In the results shown in Fig. 3, there was a 10% high stress and a 90% low stress with the first stress transition occurring at 9 years and the second occurring at 10.0 years. This time varying stress has a MTF of 45.75 years. In the results shown in Fig. 4, there was a 50% high stress and a 50% low stress with the first stress transition occurring at 5 years and the second occurring at 10.0 years. The MTF was 26.68 years. In the results shown in Fig. 5, there was an 80% high stress and a 20% low stress with the first stress transition occurring at 2 years and the second occurring at 10 years. The MTF was 18.84 years.

It can be concluded from these simulations that including the time-varying stress when predicting the actual MTF can have a dramatic effect on the actual MTF with well over a 300% change in the MTF with even a relatively modest time-dependent change in stress. Correspondingly, though not shown in these simulations, if the actual stress is more than the nominal use stress for even a relatively small amount of time, the system will age more rapidly than under nominal use stress.

V. CONCLUSION

Inclusion of the time-dependent stress in the prediction of reliability can dramatically improve the accuracy of lifetime predictions. Simulation results showed over a 300% improvement in accuracy when considering even a modest time-varying stress situation and the results would be even more dramatic under many realistic use conditions. If real-time stress history is monitored throughout the life of a part and used to establish dynamic stress guard bands, significant improvements in performance will often be possible without compromising target reliability of a system.

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