Influence of Temperature on the Standard Deviation of Electromigration Lifetimes

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***Abstract*—The electromigration (EM) lifetime standard deviation dependence on temperature for copper damascene interconnects is investigated. An analytical expression for the standard deviation as a function of temperature is obtained based on error propagation analysis applied to a typical EM-induced void growth model. It is shown that good agreement with experimental results is obtained. Furthermore, the impact of such an analysis on the extrapolation of EM lifetimes to use conditions is discussed.**

I. Introduction and Motivation

Electromigration (EM) is one of the main reliability issues for interconnects in modern integrated circuits. It normally triggers a failure due a significant resistance increase caused by the formation and the growth of voids in a metal line of the interconnect structure [1].

Characterization of EM failures are performed using experiments at accelerated conditions. Therefore, in order to estimate the interconnect lifetime under a specific use condition the failure times (TTF) obtained from the accelerated tests have to be extrapolated to the real operating current density and temperature. The extrapolation of accelerated EM lifetimes to use conditions is carried out by [1]

$$TTF_{use} = t_{50}^{test} \left(\frac{j_{test}}{j_{use}}\right)^n \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{test}}\right)\right] \times \exp\left[z(p_{max})\sigma\right], \tag{1}$$

where "$test$" refers to quantities at the accelerated test conditions and "use" at the operating conditions, t_{50}^{test} is the experimental MTTF, j is the current density, n is the current density exponent, E_a is the activation energy of the dominant failure mechanism, k is the Boltzmann constant, T is the temperature, σ is the lognormal standard deviation, and $z(p_{max})$ is the inverse of the normal cumulative distribution function (CDF) at a given maximum tolerable failure percentile p_{max}. The last term in (1) is needed to extrapolate the MTTF of the accelerated test to the very small failure percentiles at operating condition.

The key parameters to accomplish the extrapolation are the current density exponent n, the activation energy E_a, and the TTF standard deviation σ. This extrapolation methodology requires that the failure mechanisms, or more generally, the dominant physical effects at the accelerated tests remain the same at the use conditions. This implies that the parameters extracted from the experiments are also valid at normal operation. Consequently, n, E_a, and σ are assumed to be constants in regard to variations of the current density, temperature, and failure percentile for the specific failure mechanism of interest.

The current density exponent and the activation energy have been the main focus of investigations [2], [3]. Lately, a significant effort has been put in characterizing the bimodality of EM lifetime distributions, so that the above parameters are determined for each failure mode independently [2], [4], [5]. Similarly, variations of the TTF standard deviation have been mostly investigated in experiments dealing with the analysis of the different failure modes. Little has been reported in regard to modeling of standard deviation variations with changes in the test/operating conditions, in particular for the TTF standard deviation dependence on the temperature.

Thus, in this work we investigate the variation of the standard deviation of EM lifetimes as a function of temperature. Justison [6] carried out an extensive analysis of EM failures as a function of temperature in Cu single-damascene line/via structures. Therefore, his experimental results will be used as basis for comparison with the theoretical calculations performed here. An analytical expression for the standard deviation as a function of temperature is obtained based on error propagation analysis applied to a typical EM-induced void growth model. It nicely predicts the standard deviation change with temperature observed experimentally. Furthermore, the impact of such an analysis to the EM lifetime extrapolation procedure is discussed.

II. Calculation of the Lognormal Standard Deviation of EM Lifetimes

Justison [6] observed that EM failures for downstream electron flow were caused by large voids under the via, as depicted in Fig. 1. The void grows along the line, as vacancies driven by EM are captured. For a void spanning the whole line cross section the drift velocity of the void front is determined by the velocity at which the vacancies are captured, yielding [7]

$$v_d = \frac{L_v}{t} = \frac{eZ^*\rho j D}{kT}, \tag{2}$$

where L_v is the void length, t is the time, eZ^* is the effective charge, ρ is the metal resistivity, and D is the effective vacancy diffusivity. As the void grows, the electric current is forced to flow through the thin barrier layer which has a larger

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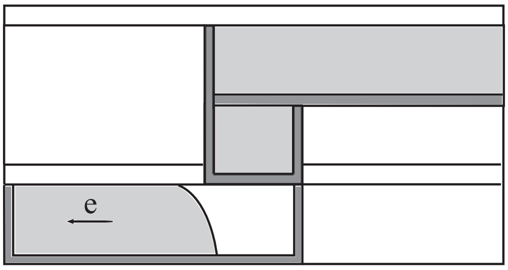

Fig. 1. Cu single-damascene structure. A large void under the via triggers EM failure.

resistivity than the copper. Consequently, the total resistance of the interconnect increases. The resistance of the line can be written as

$$R = R_{Cu} + R_b = \frac{\rho(L - L_v)}{A} + \frac{\rho_b L_v}{A_b}, \tag{3}$$

where L is the line length, A is the copper cross sectional area, ρ_b is the barrier resistivity, and A_b is the barrier cross sectional area. The first term on the right-hand side is the resistance due to the remaining Cu line and the second term is the additional resistance for the current to flow through the barrier. The resistance change is then given by [8]

$$\frac{\Delta R}{R_0} = \frac{R - R_0}{R_0} = \left(\frac{\rho_b A}{\rho A_b} - 1\right)\frac{L_v}{L}, \tag{4}$$

where R_0 is the initial resistance. This expression provides a relationship between the void length and the resistance change of the line. When the resistance increase reaches a certain critical value the interconnect is considered to have failed. The corresponding critical void size can be estimated from (4) giving

$$L_c = L\left(\frac{\rho_b A}{\rho A_b} - 1\right)^{-1}\left(\frac{\Delta R}{R_0}\right)_c. \tag{5}$$

Using (2), the failure time is then given by

$$t_f = \frac{L_c kT}{eZ^* \rho j D}, \tag{6}$$

with L_c obtained from (5). Expressing the diffusivity through an Arrhenius equation we can write

$$t_f = \frac{L_c kT}{eZ^* \rho D_0}\frac{1}{j}\exp\left(\frac{E_a}{kT}\right), \tag{7}$$

where D_0 is the diffusivity pre-factor. Note that (7) has the same form as Black equation with $n = 1$ [9], since this failure scenario is governed by the void growth kinetics.

Taking the logarithm of (7) yields

$$\ln(t_f) = \ln\left(\frac{L_c kT}{eZ^* \rho D_0}\frac{1}{j}\right) + \frac{E_a}{kT}, \tag{8}$$

which can be written as

$$\ln(t_f) = b + \frac{E_a}{kT}, \tag{9}$$

for $b = \ln(L_c kT/eZ^* \rho j D_0)$.

(9) is the base for the activation energy extraction in typical EM experiments. Although it is commonly used to extract the activation energy based on the MTTF (50% cumulative failure probability), it can be applied to extract E_a at any failure percentile. In this way a distribution of E_a is obtained and characterized by a mean value $\bar{E}_a$ and a standard deviation σ_E. Similarly, this procedure allows the calculation of a distribution of b characterized by a mean $\bar{b}$ and a standard deviation σ_b. Once σ_E and σ_b are determined, the lognormal standard deviation of the EM lifetimes can be theoretically estimated. Applying error propagation analysis to (9) yields [10]

$$\sigma_t^2(T) = \sigma_b^2 + \left(\frac{1}{kT}\right)^2 \sigma_E^2 + \frac{1}{kT}\mathrm{cov}(b, E_a), \tag{10}$$

where σ_t is the lognormal standard deviation of the EM lifetimes and $\mathrm{cov}(b, E_a)$ is the covariance between b and E_a. (10) can be used to estimate the change of the EM lifetime standard deviation as a function of temperature. This approach provides a more precise prediction of the standard deviation at the real operating temperature, which also leads to a more reliable TTF extrapolation.

III. Results and Discussion

The EM lifetime distributions for several temperatures are shown in Fig. 2. The plotted data have been extracted from the experimental results from Justison [6]. The TTF is well fitted by a lognormal distribution for all test temperatures. A decrease in the slope of the fitted curve at lower temperatures can be seen, which implies that the TTF standard deviation has increased. The fitted MTTF and standard deviation calculated from the extracted data are given in Table I, which clearly shows that there is a significant increase in the TTF standard deviation as the temperature decreases.

The experimental TTF standard deviation shown in Table I is now compared with the theoretical calculations with (10). Using the lognormal distribution equations obtained from the

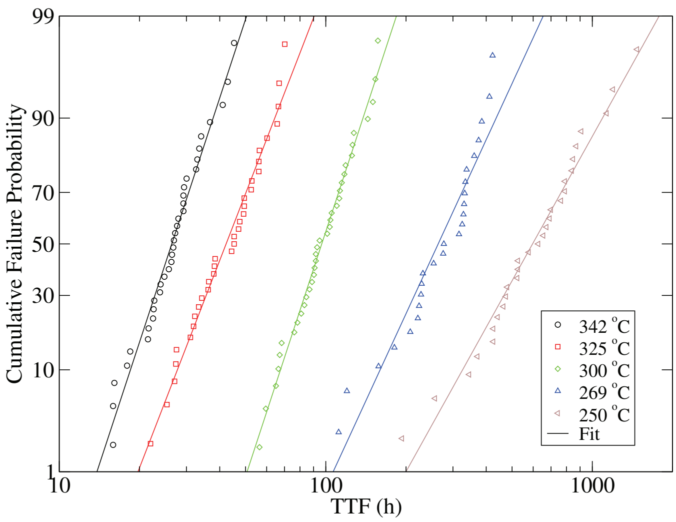

Fig. 2. EM lifetime distribution of a Cu damascene structure for different test temperatures. The plotted data are extracted from [6].

TABLE I

FITTED MTTF AND STANDARD DEVIATION FOR THE DATA OF FIG. 2.

T (°C)	MTTF (h)	σ
250	596	0.47
269	264	0.39
300	96.6	0.28
325	42.3	0.33
342	26.4	0.28

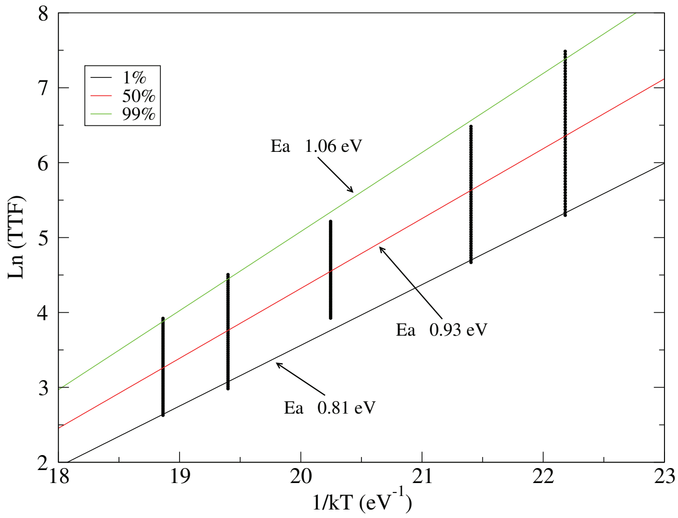

Fig. 3. Activation energy estimation. Fitting (9) for several percentiles yields a distribution for E_a and a distribution for b.

fitting of the TTF data shown in Fig. 2, we can determine the TTF at each temperature for the exact same cumulative failure percentiles. The results are plotted in a $\ln(t_f) \times 1/kT$ graphic, as shown in Fig. 3.

By fitting (9) to the MTTF data an activation energy of 0.93 eV is estimated. This is a typical value found for EM failures in Cu interconnects, where the Cu/capping layer interface acts as the dominant material transport path. However, an activation energy of 0.81 eV and 1.06 eV has been extracted for the 1% and 99% failure percentile, respectively. These values deviate significantly from the mean activation energy and such deviations have surely a significant impact on the rate of void growth, cf. (2), and, consequently, a relevant influence on the interconnect lifetime.

This variation of the activation energy is measured due to the large change of the TTF standard deviation with temperature. If the TTF standard deviation were approximately independent of the temperature, the slope of the curves in Fig. 3 would be closer to the mean value, that is, the variation of E_a about its mean value would be smaller.

It should be pointed out that the variation of E_a occurs even though the failure mechanism (growth of a large void under the via by front displacement) remains the same. Therefore, the dispersion of the activation energy can be regarded as a measure of the dispersion of the diffusivity of the lines. This is expected, because different lines have different microstructural properties and grain orientations, which leads to variations of the effective diffusivity [3]. This is in agreement with the observations of Hauschildt *et al.* [1], who showed that the diffusivity dispersion plays a major role on the TTF dispersion.

By extracting E_a values for several failure percentiles from Fig. 3 we obtain a mean for the activation energy $\bar{E}_a = 0.93$ eV and a standard deviation $\sigma_E = 0.05$ eV. Similarly, fitting (9) to the data of Fig. 3 yields a mean $\bar{b} = -14.3$ and standard deviation $\sigma_b = 0.73$ for the parameter b. Both, E_a and b are assumed to be normally distributed. In this way, $\ln(t_f)$ also follows a normal distribution, because the sum of two normally distributed variables results in a normally distributed variable [10]. In addition, since $\ln(t_f)$ is normally distributed, the failure times t_f follow a lognormal distribution [10], which is consistent with the curves shown in Fig. 2.

Substituting σ_E and σ_b in (10), the lognormal standard deviation of EM lifetimes as a function of temperature is calculated, as shown in Fig. 4. (10) nicely describes the experimental standard deviation change with temperature, thus providing a good description for the decrease of the EM lifetime standard deviation with increasing temperature. Table II shows a comparison between the experimental and the calculated standard deviations for the temperatures used in the EM tests. In general, the calculated values are in good agreement with the experimental ones. A larger difference is observed only for $T = 300°$C, where the experimental value seems to have deviated from the expected behavior.

In typical EM experiments tests are carried out for a few temperatures around 250°C – 300°C. The parameters extracted

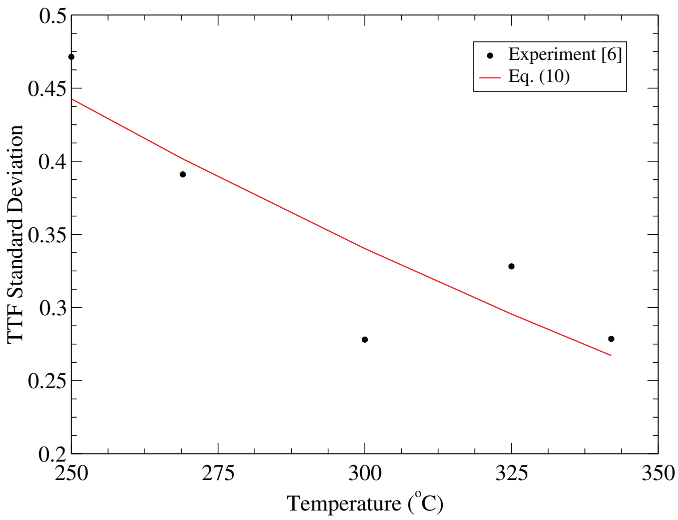

Fig. 4. EM lifetime standard deviation as a function of temperature.

TABLE II

COMPARISON BETWEEN THE EXPERIMENTAL AND THE CALCULATED LIFETIME STANDARD DEVIATIONS.

T (°C)	Experimental σ	Calculated σ	Difference (%)
250	0.47	0.44	6.4
269	0.39	0.40	2.6
300	0.28	0.34	21.0
325	0.33	0.30	9.1
342	0.28	0.27	3.6

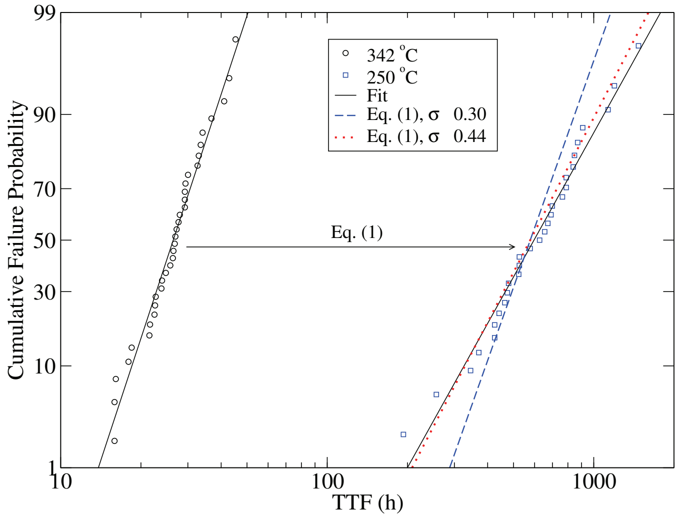

Fig. 5. Extrapolated EM lifetime distribution.

at these conditions are used in (1) to extrapolate the lifetimes to use temperatures which lie about 100°C. This makes a temperature difference of approximately 150°C.

In order to reproduce this procedure, we carry out a lifetime extrapolation from an assumed test temperature $T_{test} = 342°C$ to the hypothetical use temperature $T_{use} = 250°C$. Note that this makes a temperature difference of "only" 92°C (in comparison to the expected 150°C). In this way, we can evaluate the extrapolation procedure within the temperature range for which we know the experimental results. The parameters applied in (1) are: $t_{50}^{test} = 26.4\text{h}$, $\sigma = 0.30$ (see Table I), $j_{test} = j_{use}$ (the current density is the same at all temperatures, so it does not affect the extrapolation), and $E_a = 0.93$ eV. The extrapolation is performed for $1\% \leq p_{max} \leq 99\%$, which yields a distribution for the extrapolated TTF. The results are shown by the dotted blue line in Fig. 5. Apart from the MTTF, this extrapolation does not provide, in general, a very good description for the EM lifetime distribution at 250°C. The error is particularly large for the early failures, which is critical considering that the reliability of an interconnect is normally determined by these low percentile failures.

Fig. 5 also shows the extrapolation results obtained using $\sigma = 0.44$, as calculated from (10). Due to the small error between the calculated and the experimental standard deviation (see Table II), the extrapolation in this case leads to a very good approximation of the lifetimes for $T = 250°C$. Note that the use temperature of $T_{use} = 250°C$ is significantly larger than the real operating temperature ($\sim 100°C$). Thus, an even larger error is expected, when the extrapolation is performed with the standard deviation extracted from the accelerated tests.

An important advantage of the the method presented above is that it is based on standard EM experiments for extraction of the activation energy. However, a careful analysis of the experimental data has to be performed to properly identify and separate different failure modes, so that the observed variation of the standard deviation is not caused by two different failure mechanisms. In order to obtain a more precise reliability assessment of interconnects regarding EM induced failures, it is crucial that the accelerated tests are carried out over a wide range of temperatures and as close as possible to the use temperature. In this way the study performed here can offer a valuable help in tracking standard deviation changes as a function of the temperature and providing more reliable parameter estimates for the extrapolation procedure.

IV. Conclusion

It has been shown that the variation of the EM lifetime standard deviation with temperature has an important impact on the prediction of lifetimes at use conditions. In order to track this variation a model based on error propagation analysis has been studied. The model correctly describes the increase of the standard deviation of EM lifetimes as the temperature decreases. The theoretical calculations are in good agreement with the experimental results. Extrapolation of EM lifetimes from accelerated tests using the experimental standard deviation estimation is likely to produce large errors in the extrapolated lifetimes. The methodology described in this work yields a better estimation of the standard deviation to be applied in the extrapolation, which results in a more precise prediction of the EM reliability.

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