Statistical Modeling of Via Redundancy Effects on Interconnect Reliability

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Abstract – **Electromigration is an important failure mechanism in the nano-interconnects of modern IC technology. Various approaches have been investigated to prolong the lifetime of an interconnect. One such approach is to have an in-built redundancy in the via structures of the interconnect. The presence of redundant via in a parallel topology helps improve the overall reliability of the via structure. Although reliability improvement due to via redundancy is qualitatively understood, it is necessary to quantify the improvement in reliability through statistical models so that the improvement in lifetime as a result of redundancy can be quantified. A statistical model that incorporates the effects of redundancy is developed in this study and it is used to estimate the reliability of redundant via structures. The Cumulative Damage Model (CDM) is used in conjunction with the Maximum Likelihood Estimate (MLE) method to assess the reliability of load sharing via redundant structures in this study.**

I. INTRODUCTION

As the integrated circuit technology undergoes continued downscaling in accordance to Moore's law to achieve improvements in device and circuit performance and to miniaturize electronic products, many reliability issues have become very critical to the long-term performance of these nanodevices. One of these critical failure mechanisms affecting reliability is electromigration (EM) in the back-end interconnect lines [**1**].

Electromigration refers to the current-induced atomic flux due to momentum exchange between the electrons and atoms that causes atomic flux from the cathode to the anode terminal. There are various driving forces causing EM some of which include the electron wind force, stress gradients due to hydrostatic stress variations in the interconnect as a result of the thermal coefficient mismatch between various materials in the interconnect structure induced by high temperature process conditions, back flow stresses as well as temperature gradients that arise as a result of the Joule heating effect [**2**]. Increasing atomic accumulation at the anode causes compressive stresses and depletion of atoms at the cathode leads to vacancies which coalesce to form voids. A steady state is achieved when the atomic fluxes induced by the various driving forces sum up to zero which results in a time-invariant stress profile provided that the peak stresses at steady state are lower than the critical stresses required for cathode void nucleation [**2**].

The most critical element of an interconnect structure is the via which connects different levels of metallization. The via which has a smaller cross-section than the lines is subject to higher current densities causing it to fail sooner than the lines [**3**]. In order to improve the overall via reliability, redundancy is incorporated into the via structures by having more than one via connected in parallel in a load sharing configuration so that the multiple via share the current flow. This active load sharing redundancy illustrated in Fig 1 reduces the current density load per via when all the via are operating thereby prolonging their time to failure. After one via fails, subsequent via experience higher current density stresses by sharing the extra current load which the failed via was previously subjected to causing them to then fail sooner. On the whole, via redundancy effects help achieve substantial improvements in interconnect reliability. This is especially the case in Cu dual damascene systems where the via are also made of Cu unlike Al interconnect technology where the via is made of Tungsten (W) which has an intrinsically high electromigration resistance [**2**].

Having fabricated redundant via structures, it is necessary to quantify the improvement in reliability as a result of the redundancy incorporated. This requires the use of concrete statistical models [**4**]. Although some literatures in the past have assessed the reliability of redundant via structures [**5**] – [**7**], very few have modeled it from a statistical perspective. The statistics describing reliability of redundant via structures is complicated because the nature of degradation cannot be described by a single distribution. As an example, for a two-via system, the failure distribution of both via prior to any one of them failing is different from the failure distribution of one of the via after the other has failed. Therefore, given the different stresses experienced by the via during its lifetime, the distribution of the via elements and the via system need to be modeled in a statistically precise manner.

In this study, we use a robust technique known as the *cumulative damage model* (CDM) [**4**] in conjunction with the conventional *maximum likelihood estimate* (MLE) [**8**] method to account for the time-varying stress profile [**9**] of the via elements during accelerated life test of a via redundant system. Based on these statistical tools the reliability of each "via element" is first estimated. This is followed by an estimation of the reliability of the "via system" based on the "via element" reliabilities accounting for the effect of load sharing in the system.

The structure of this paper is organized as follows. Section II introduces the via load sharing redundant system and analyzes the typical stress profile that the via elements could be subjected to during the accelerated stress tests. Section III presents the cumulative damage model (CDM) along with the life-stress relationship used for accelerated testing of via test structures. Section IV develops the likelihood expression for the via elements based on the CDM model developed. This expression is then optimized based on the maximum likelihood estimate (MLE) method. The values of the statistical distribution parameters which optimize the likelihood function are then used to evaluate the reliability of each via element. In Section V, the reliability of the overall via system is evaluated accounting for the effect of load sharing redundancy. Section VI presents some simulation results obtained based on the theory prescribed above. Finally, the last section concludes with an assessment of the statistical model used and the assumptions it is based upon.

II. STRESS PROFILE IN A LOAD SHARING REDUNDANT SYSTEM

The system in Fig 1 is an *active load sharing redundancy* system wherein the operating via elements share the current density flow equally at time t = 0. The value of current density flowing through each via with time, j(t), depends on the number of unfailed via in the load sharing system, their relative resistance degradation trends and their relative void growth rates due to the EM phenomenon.

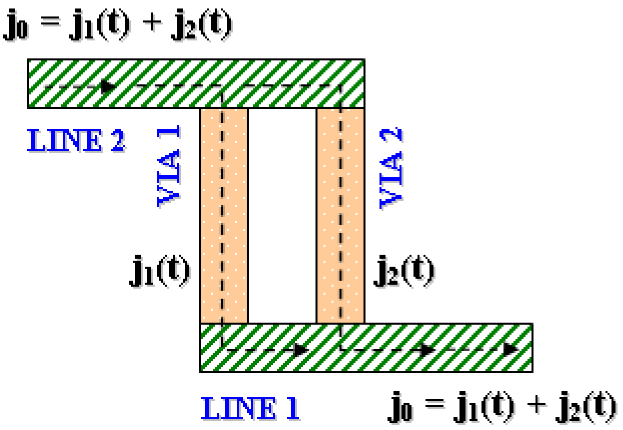

Fig. 1. Load sharing via redundant system for a constant overall current density stress of j_0 = 2 MA/cm^2. The current density stresses through the via elements VIA 1 and VIA 2 depend on the relative resistance degradation of the via elements and the relative rates of the EM induced void growth.

Assuming the resistance of via elements VIA 1 and VIA 2 to be $r_1(t)$ and $r_2(t)$ and given the constant overall current density stress of j_0 = 2 MA/cm^2, the current splits into $j_1(t)$ and $j_2(t)$ based on the current divider principle as given by (1) and (2). As the resistance of the via elements degrade at different rates and as their voids grow at different rates reducing the effective cross-sectional area for current flow, the current density stress changes as a function of time in both the via elements. The total current density stress however remains fixed at j_0 = 2 MA/cm^2.

$$j_1(t) = \left[\frac{r_2(t)}{r_1(t)+r_2(t)}\right]\cdot j_0 \tag{1}$$

$$j_2(t) = \left[\frac{r_1(t)}{r_1(t)+r_2(t)}\right]\cdot j_0 \tag{2}$$

The typical stress profile encountered by a via element in the redundant via system is given by Fig 2. This stress profile indicates a *time varying current density stress* in the via elements and this effect of continuous time varying stress is accounted for in the CDM model. The CDM model considers the cumulative effect of stresses experienced by an element through its lifetime up to failure.

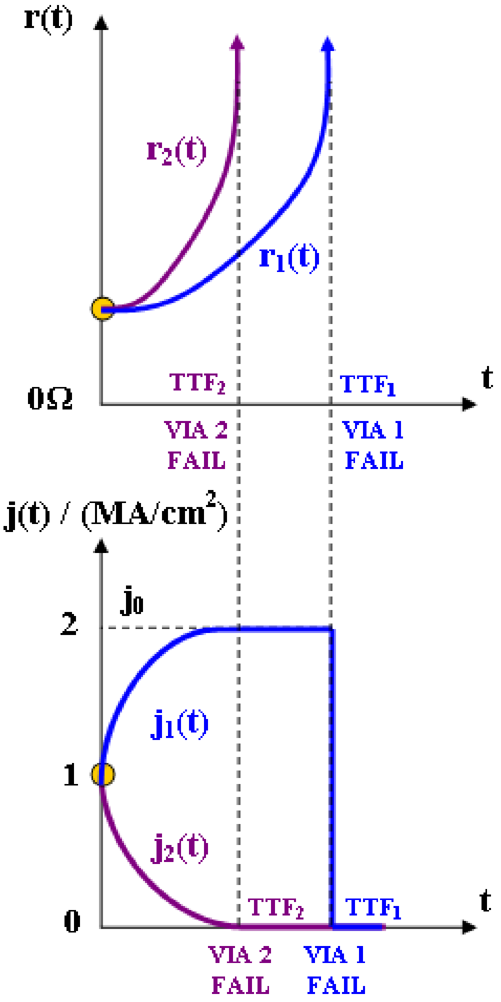

Fig. 2. Typical profiles of resistance degradation and the resulting current density stresses in a two-via redundant load sharing test structure subjected to a constant overall current density stress of j_0 = 2 MA/cm^2. The current density profile in the via elements is given by Eq. (1) and Eq. (2). In this case, VIA 2 degrades faster and fails open first at t = TTF_2 following which VIA 1 takes in all the current causing it to degrade faster and eventually fail at t = TTF_1. The complete via system is considered to have failed at t = TTF_1.

III. CUMULATIVE DAMAGE MODEL

For accelerated EM life tests at a given interconnect temperature, we model the scale parameter of an element to depend on the current density stress level experienced by it using the inverse power law life-stress relationship given by (3) where L refers to the scale parameter of the distribution [**4**]. Eq. (3) suggests that for an instantaneous stress, j(t), at a time interval t to (t + Δt), the failure distribution of the unfailed via elements at time t is represented by a scale parameter, L(t) corresponding to j(t). Therefore, for every instantaneous time interval Δt, the scale parameter, L(t), is different since the stress level and its associated failure distribution at that Δt time interval is different. Based on this scenario, the scale parameter is modeled as a time-varying function that depends on the time-varying stress as given by (3).

Since the process of void nucleation and growth in every via is gradual, the failure of the via element is well represented by the Lognormal distribution [**10**]. Therefore, the scale parameter (L) in (3) refers to the median life, t_{50}, for the Lognormal distribution..

It is to be noted that although current density is the only stress factor considered, the varying current densities across the redundant vias are likely to result in different local temperature stresses as a result of the Joule heating effect. In this work, we ignore the non-uniformity in the temperature of the redundant vias as a result of Joule heating and assume that current density is the only variable stress factor.

$$L[t, j(t)] = \frac{1}{K \cdot [j(t)]^n} \tag{3}$$

Based on (3), the via element reliability may be expressed by (4) accounting for the stress dependence and its variation with time. The integral in (4) denotes the cumulative effect of the time-varying current density stress damage experienced by the via element. The parameter σ is the shape parameter of the Lognormal distribution and it is assumed to be constant for all stress conditions since it is indicative of the failure mechanism [**11**] which is assumed to remain the same for all applied and field stress conditions.

$$R[t, j(t)] = 1 - \Phi\left(\frac{1}{\sigma}\ln\left(\int_0^t \frac{dt}{L[t, j(t)]}\right)\right) \tag{4}$$

IV. MAXIMUM LIKELIHOOD ESTIMATE

Having modeled the reliability, R(j, t), as a function of time and the time-varying current density stress level, the log-likelihood function of every via element may be expressed by (5) where $T_{F,i}$ represents the time to failure of the i^{th} via element, $T_{S,j}$ is the censor or suspension time of the j^{th} via element, κ is a constant and LKL is the log-likelihood function [**8**]. In (5), f(t) is the probability density function which is given by –dR(t)/dt. F denotes the number of via element failures observed while S refers to the number of censored units. Note that we have so far been analyzing individual via elements in the redundant via structure. The quantity (F + S) is the total number of redundant via structure units tested. The failure and suspension times are measured for every via element in the (F + S) via structures that are subjected to the accelerated test.

$$LKL = \sum_{i=1}^{F} \log\left(f\left(T_{F,i}\right)\right) + \sum_{j=1}^{S} \log\left(R\left(T_{S,j}\right)\right) + \kappa \tag{5}$$

Given the log-likelihood function, the set of parameters {σ, K, n} that optimize the log-likelihood function may be found using various optimization techniques such as the Quasi-Newton method or the global optimization simulated annealing algorithm. The equations representing the optimization problem are given by (6).

$$\frac{\partial LKL}{\partial \sigma} = \frac{\partial LKL}{\partial K} = \frac{\partial LKL}{\partial n} = 0 \tag{6}$$

Based on Eq. (6), the parameters {σ, K, n} for every via element may be obtained and the individual via element reliability functions are fully described. Having quantified the reliability functions of the individual via elements, the reliability of the overall redundant via structure needs to be determined.

V. LOAD SHARING SYSTEM RELIABILITY

The "system reliability" of the load sharing redundant via structure for a simple two-via system may be expressed as in (7) where the expressions for $R_{1\&2}$, $R_{1/2}$ and $R_{2/1}$ are given by (8), (9) and (10) respectively. The expression in (7) implies that a two-via system could be operating under three conditions. Either both the vias are functioning or one of them has failed while the other is functional. Equation (8) denotes the system reliability when both VIA 1 and VIA 2 are functional. Equations (9) and (10) refer to the system reliability under cases of VIA 2 functioning while VIA 1 failure and VIA 1 functioning while VIA 2 failure respectively.

$$R_{system}(t, S) = R_{1\&2}(t, S) + R_{1/2}(t, S) + R_{2/1}(t, S) \tag{7}$$

$$R_{1\&2}(t, S) = R_1(t, S_1) \cdot R_2(t, S_2) \tag{8}$$

$$R_{1/2}(t, S) = \int_0^t f_1(x, S_1) \cdot R_2(x, S_2) \cdot \frac{R_2(t_{1e} + (t - x), S)}{R_2(t_{1e}, S)} dx \tag{9}$$

$$R_{2/1}(t, S) = \int_0^t f_2(x, S_2) \cdot R_1(x, S_1) \cdot \frac{R_1(t_{2e} + (t - x), S)}{R_1(t_{2e}, S)} dx \tag{10}$$

In (5) – (8), S is the total current density stress the via system is subjected to and S_1 and S_2 are the corresponding fractions of the total stress that VIA 1 and VIA 2 experience respectively.

The parameter t_e denotes the equivalent operating time of an element if it had been operating at a different stress level.

VI. STATISTICAL ANALYSIS OF REDUNDANT VIA SYSTEM

To illustrate the application of the above theory, a sample of test data from an electronic device with built-in redundancy was obtained [**4**]. This set of data is assumed to hold true for the two-via EM test structure examined here. The overall current density stress is taken to be 2 MA/cm^2 while the temperature during the stress test = 300^{0}C. Although current density and temperature are both acceleration factors in general for any EM test, the temperature stress of the line is kept fixed and joule heating induced temperature changes are also ignored making current density the only acceleration factor of focus. The failure data and the predicted stress profile, shown in Fig 2, for both the via elements in the via system are used and statistical analysis is then performed by optimizing the log-likelihood function in (5).

As a first attempt to model the impact of via redundancy statistically, for the sake of illustration and simplicity, we assume that the reliability functions for the two via elements are similar and therefore the failure data for these two via are treated collectively. However, in actual test conditions, the two vias will not be identical since they have different boundary conditions. Optimization of the log-likelihood function results in the values for σ = 0.7744 and n = 0.8072. The Lognormal probability plot for the via element in the presence of a load sharing redundancy is shown in Fig 3. The plot reveals a good lognormal fit to the tested failure data.

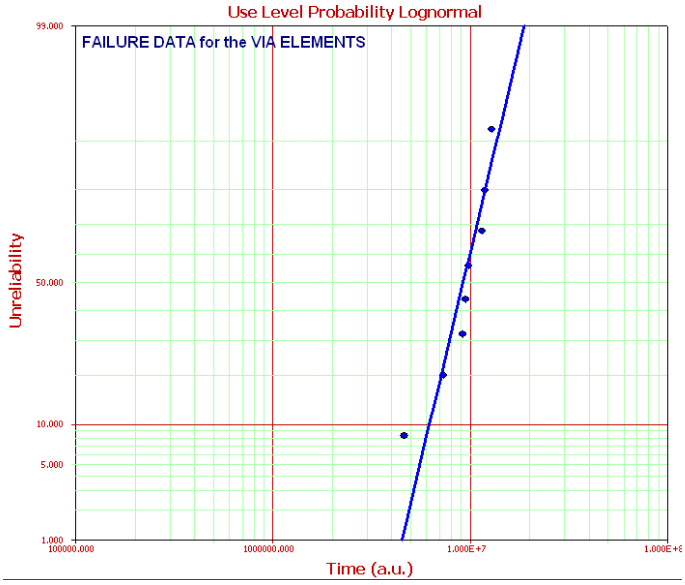

Fig. 3. Lognormal probability plot for the via elements at the use stress level of 0.5 MA/cm^2.

Having characterized the reliability of the individual via elements, we may determine the reliability of the "via system" for any given stress condition by using (7) – (10) where the stresses S_1 and S_2 are expected to be changing with time depending on the resistance degradation profiles of the individual via elements. Assuming for illustrative purpose that the two via elements each carry 50% of the total current load, the system reliability curve for the overall load sharing system at the field operation stress of 0.5 MA/cm^2 is given in Fig 4. Since the reliability of the via elements degrade gradually, the overall resistance degradation behavior of the via system is also expected to be gradual and hence via redundant system may also be well represented by the Lognormal statistics.

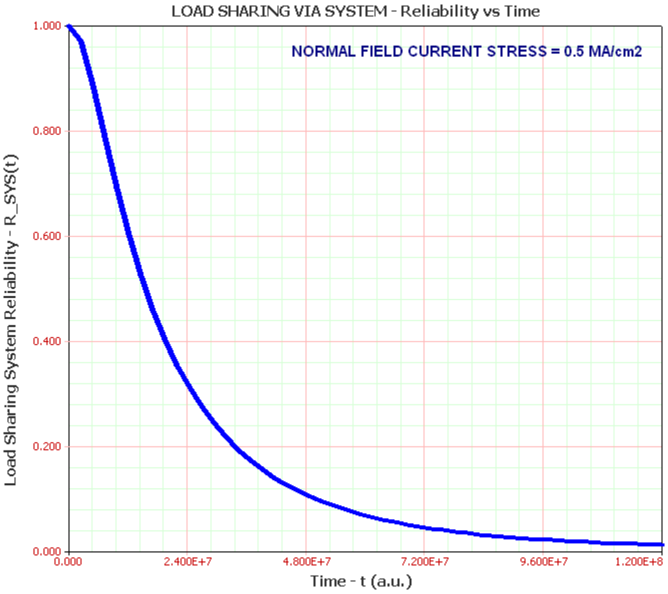

Fig. 4. Reliability function of the overall load sharing via redundancy system for a field stress of 0.5 MA/cm^2 and assuming that both the via elements share 50% of the load for all times up to failure.

VII. CONCLUSION

The novelty and usefulness of the CDM model has been illustrated in this work highlighting the theory involved and the way it accounts for the accumulated damage as a result of time varying stresses. Although the CDM model may not be necessary in the case of single via or single EM line tests where the current density stress is bound to be constant throughout, it is a very useful approach to model redundant via systems wherein the current densities through the individual via elements is bound to change depending on the relative resistance degradation rates of the load sharing via elements. The approach presented in this work may be further extended to analyze and quantify the improvement in reliability that may be observed as the number of via in the EM structure is increased. This is the first work of its kind that explicitly models the impact of via redundancy using a reliability block diagram (RBD) approach.

Although the CDM model appears robust and convenient for use, there are a few inherent assumptions [**12**] that it is based upon and it is important to take note of these. The theory we have used thus far only applies to the case if there is a single failure mechanism present. Moreover, the model does not account for failures that could occur during sudden instantaneous changes in stress levels, if any, as is the case for step-stress tests. Lastly, the presented version of the CDM model is not capable of accounting for small cyclic changes in the stress levels about a given mean stress which is often the case during fatigue.

It is hoped that this work serves as motivation for further statistical modeling and analysis into the effects of via redundancy. Further research work is under way to consider the effect of multiple failure mechanisms on the CDM model since most EM structures are subjected to bimodal failure distributions and also account for the effect of joule heating while assessing the statistical reliability of redundant via systems.

ACKNOWLEDGMENT

The authors would like to thank the *Nanoelectronics Design Lab, School of EEE, Nanyang Technological University (NTU), Singapore* for access to *Reliasoft*® *Inc.* software tools that were used to perform the reliability data analysis simulations in this work.

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