A Compact Model for Early Electromigration Lifetime Estimation

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***Abstract*—A compact model for early electromigration failures in copper dual-damascene M1/via structures is proposed. The model is derived based on relevant physical effects of the early failure mode, where a rigorous void nucleation model and a simple mechanism for slit void growth are considered. As a result, a simple analytical model for the early electromigration lifetime is obtained. In addition, it is shown that the simulations provide a reasonable estimation for the early lifetimes.**

I. INTRODUCTION

Electromigration (EM) is one of the major reliability issues for modern integrated circuits. EM normally triggers a chip failure due to formation and growth of voids in a metal line of the interconnect structure [1]. Experimental works have observed two distinct EM failure modes in copper dual-damascene interconnects, namely the late (strong) mode and the early (weak) mode [2]. The late failure mode is characterized by the growth of a void spanning the line cross section. In turn, in the early failure mode a slit void under the cathode via is typically observed [3].

These two failure mechanisms are considered to be the origin of the bimodal distribution commonly observed in copper dual-damascene interconnects, where the EM lifetime of each mode is characterized by its own statistical properties. Moreover, the kinetic behavior also depends on the failure mode. It has been shown that the late mode is dominated by the void growth mechanism, while the early mode is governed by the combination of the nucleation and the growth mechanism [4].

A typical reliability criterion allows one failure in 10^9 hours of device operation [2]. This means that interconnect reliability against EM is primarily determined by the early failures. Thus, modeling and understanding of the early failure mode becomes crucial for a precise reliability assessment.

In this work a compact model for early EM failures in copper dual-damascene M1/via structures is developed. The model is based on the combination of a complete void nucleation model together with a simple mechanism of slit void growth under the via. It is demonstrated that the early EM lifetime is well described by a simple analytical expression, from where its statistical distribution can be obtained. Moreover, it is shown that the simulation results provide a reasonable estimation for the EM lifetimes.

II. MODELING

EM failure is caused by formation and growth of voids in the interconnect metal. Once a void is formed, it grows and causes an increase in the line resistance. The resistance is allowed to increase, until a maximum tolerable value is reached, which is used as failure criterion. Thus, the lifetime of an interconnect line under EM is, in general, given by

$$t_f = t_n + t_g, \tag{1}$$

where t_n is the time elapsed to first nucleate a void and t_g is the void growth time. The relative contribution of each component can vary significantly depending on the interconnect technology, fabrication process, stress conditions, etc. Moreover, each component is influenced by different physical effects and shows a different kinetic behavior [5]. Therefore, modeling EM lifetimes requires the understanding of both phases of failure development.

A. Void Nucleation

Material transport in a metal line is affected not only by EM itself, but also by other accompanying driving forces. The total vacancy flux is then given by

$$\vec{J}_v = -D_v\left(\nabla C_v + \frac{eZ^*}{kT}C_v\rho\vec{j} - \frac{Q^*}{kT^2}C_v\nabla T \right.$$
$$\left. + \frac{f\Omega}{kT}C_v\nabla\sigma\right), \tag{2}$$

where D_v is the vacancy diffusivity, C_v is the vacancy concentration, e is the elementary charge, Z^* is the effective charge, ρ is the metal resistivity, $\vec{j}$ is the electrical current density, Q^* is the heat of transport, f is the vacancy relaxation ratio, Ω is the atomic volume, σ is the hydrostatic stress, k is Boltzmann's constant, and T is the temperature.

In sites of flux divergence there is accumulation or depletion of vacancies according to the continuity equation

$$\frac{\partial C_v}{\partial t} = -\nabla\cdot\vec{J}_v + G, \tag{3}$$

where G is a given source function which models vacancy annihilation and generation. In addition, vacancy transport is accompanied by the creation of mechanical strain [6]

$$\frac{\partial\varepsilon}{\partial t} = \Omega\left[(1-f)\,\nabla\cdot\vec{J}_v + fG\right], \tag{4}$$

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where ε is the trace of the strain tensor. Thus, (4) connects EM and mechanics. Since copper dual-damascene interconnect lines are confined by surrounding layers, mechanical stress develops.

In order to calculate the mechanical stress in a three-dimensional copper dual-damascene interconnect structure, (2)–(4) have to be solved together with the electro-thermal equation, the diffusion equation, and the mechanical equations. The numerical solution of these equations is indeed rather complex [7].

Korhonen *et al.* [8] proposed a simple one-dimensional model, where the solution for the stress at the cathode of a semi-infinite line is given by

$$\sigma(t) = \frac{2eZ^{*}\rho j}{\Omega}\sqrt{\frac{D_a B\Omega}{\pi kT}t} = a\sqrt{t}, \tag{5}$$

where D_a is the effective atomic diffusivity and B is the effective modulus, which depends on the metal and the surrounding materials.

Void formation occurs as soon as the mechanical stress reaches a critical magnitude at a site of weak adhesion, typically at the copper/capping layer interface [9], [10]. Thus, the void nucleation time is determined by the condition $\sigma(t_n) = \sigma_c$, which applied to (5) yields

$$t_n = \frac{\pi}{4}\frac{\Omega kT}{\left(eZ^{*}\rho j\right)^2 B D_a}\sigma_c^2 = \left(\frac{\sigma_c}{a}\right)^2, \tag{6}$$

where σ_c is the critical stress.

The solution given by (6) is a good approximation to the more complete solution obtained by solving (2)–(4) numerically, as will be shown later. It should be pointed out that this is valid as long as the stress remains significantly smaller than the stress magnitude at the steady state condition, which holds true for the void formation phase.

B. Void Growth

For a copper dual-damascene M1/via structure with downstream electron flow, EM failure analyses [3] indicate that the early failures are caused by slit voids located under the via, as shown in Fig. 1. Since the void is very thin and does not grow through the line height, void growth can be described by a one-dimensional process, so that the void length is given by

$$l_{void} = v_d\ t, \tag{7}$$

where v_d is the drift velocity of the right edge of the void.

The atomic flux into the right edge of the void is governed by the diffusivity of the copper/barrier layer interface $D_{Cu/barrier}$, while the outgoing flux is governed by the surface diffusivity D_s. Since $D_s >> D_{Cu/barrier}$, using the Nernst-Einstein equation one can write [11]

$$v_d = \frac{eZ^{*}\rho j}{kT}D_s. \tag{8}$$

The EM failure occurs, when the void spans the via size, $l_{void} = L_{via}$, so that the void growth time contribution to the EM lifetime is given by

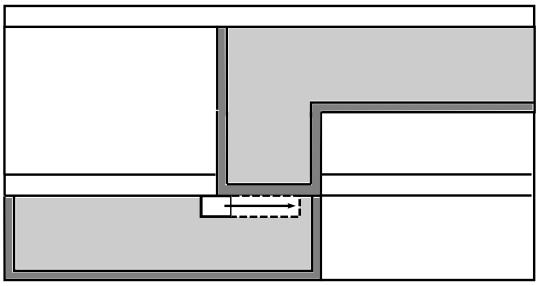

Fig. 1. Early failure mode: slit void growth under the via.

$$t_g = \frac{L_{via}}{v_d} = \frac{kTL_{via}}{eZ^{*}\rho j D_s}. \tag{9}$$

III. RESULTS AND DISCUSSION

Fully three-dimensional numerical simulations were carried out by solving (2)–(4) using an in-house finite element code. Fast diffusivity paths and microstructure are properly considered. The solution of such a model is indeed rather complex and a detailed description of the numerical approach can be found in Ref. [7].

Fig. 2 shows the mechanical stress close to the via at the cathode end of a simulated line. A high stress develops adjacent to the via, where there is a line of intersection between the copper, the capping layer, and the barrier layer. For a copper dual-damascene M1/via structure with downstream electron flow, this is the typical site for void formation and growth leading to early EM failures.

Since EM failure has a statistical character, in order to obtain a distribution of void nucleation times several lines with different microstructures were simulated. In particular, the mechanical stress under the via was monitored for a total of twenty lines, from where the resulting stress build-up for five different structures is shown in Fig. 3.

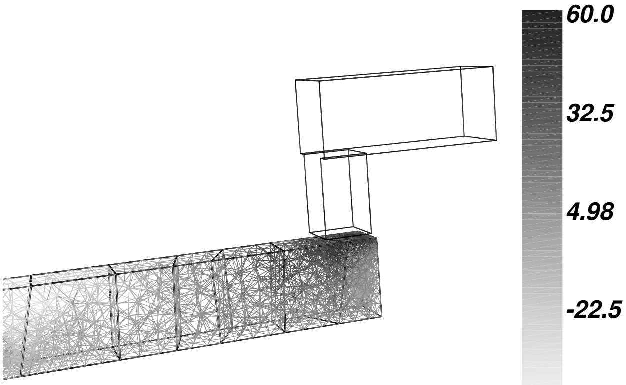

Fig. 2. Hydrostatic stress distribution (in MPa). A high stress develops at the copper/capping/barrier layer intersection adjacent to the via.

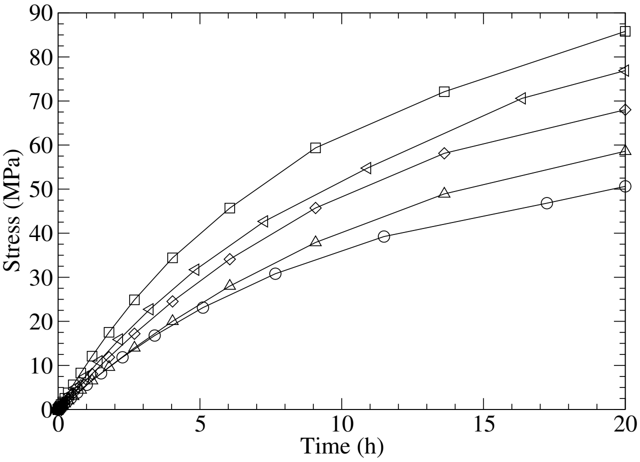

Fig. 3. Stress build-up at the copper/capping/barrier layer intersection for lines with different microstructures.

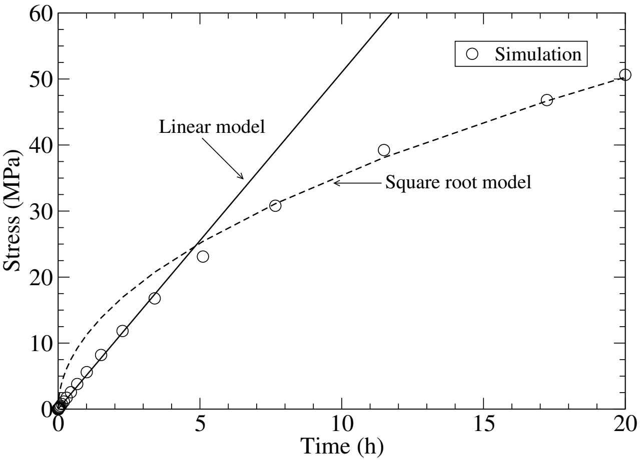

Fig. 4. Fitting of a numerical solution using a linear and a square root model.

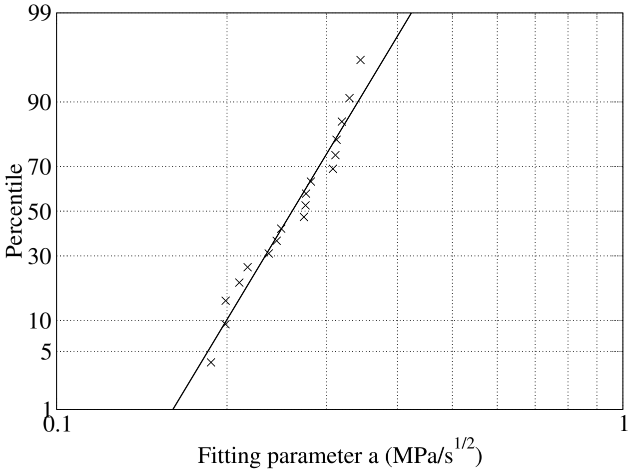

Fig. 5. Distribution of the square root model fitting parameter. The line represents a lognormal fit.

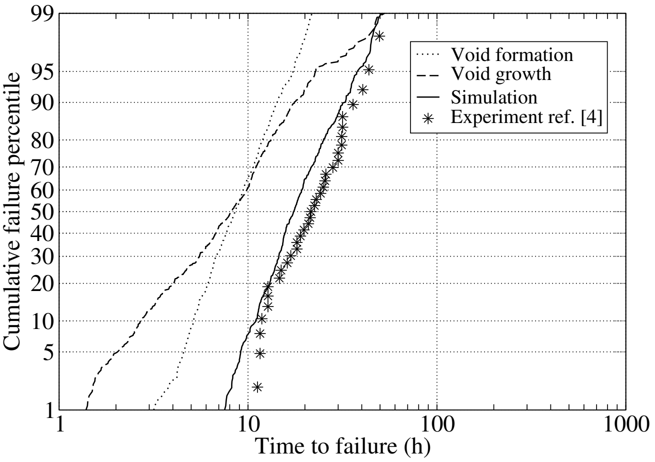

Fig. 6. Early EM lifetime distribution.

We have observed that the time evolution of the stress curves can be divided into two main parts. In the first one the stress increases linearly with time, while in the second part it increases with the square root of time, as shown in Fig. 4 for a typical stress curve. It should be pointed out that Kirchheim [12] derived a linear stress increase from a one-dimensional version of (2)–(4) under the condition that the stress is sufficiently low. In turn, Korhonen *et al.* [8] obtained a square root stress increase, as given by (5), from the solution of a simplified model for EM stress build-up. Thus, the stress build-up obtained from our numerical simulations with a rather complete model and for fully three-dimensional structures can be conveniently described by simple analytical solutions.

Since void nucleation is expected to occur at high stress magnitudes, the second part of the stress curve shown in Fig. 4 is fitted by the square root model given in (5), where a is used as fitting parameter. By fitting the stress curves of all simulated structures, the distribution of the parameter a is determined, as shown in Fig. 5. The parameter is well described by lognormal statistics, where the mean and the standard deviation are $\bar{a} = 0.23$ MPa/s$^{1/2}$ and $\sigma_a = 0.19$, respectively.

Once a is known, the void formation time is obtained from (6). Since the distribution of a is also determined, we are able to obtain the statistical distribution of the void formation times, shown in Fig. 6. Due to the lognormal statistics of a, t_n also follows a lognormal distribution, where the mean and standard deviation are $\bar{t_n} = 8.5$ h and $\sigma_{t_n} = 0.38$. It should be pointed out that Filippi *et al.* [4] estimated a nucleation time of approximately 5 hours, which lies within the range predicted by the simulations.

The void growth time is determined by (9), which is a function of the surface diffusivity. Choi *et al.* [11] obtained an activation energy for surface diffusivity of 0.45 ± 0.11 eV on clean copper surfaces. It is expected that their measurement delivers a more precise copper surface diffusivity than the typical ones obtained on oxidized surfaces [11] and, therefore, we have used their estimate in the simulations. Furthermore, we have assumed that the activation energy follows a normal distribution [13]. As a consequence, both the surface diffusivity and the void growth time are lognormally distributed.

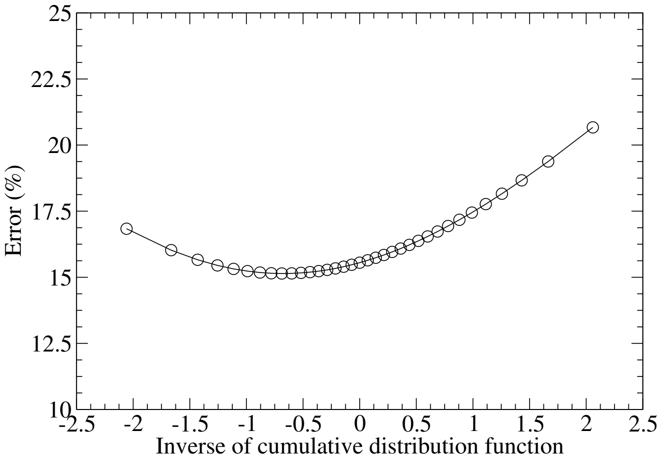

Fig. 7. Error between the simulation and the experimental results.

The mean and the standard deviation of the void growth time distribution are $\bar{t_g} = 8.0$ h and $\sigma_{t_g} = 0.7$, respectively. The void formation and the void growth times are of about the same order of magnitude, as shown in Fig. 6, which highlights the importance of considering both contributions for the early EM lifetime estimation under accelerated test conditions.

As the void nucleation and the void growth times are known, the early EM lifetime is given by the combination of (6) and (9),

$$t_f = \left(\frac{\sigma_c}{a}\right)^2 + \frac{kTL_{via}}{eZ^*\rho j D_s}. \tag{10}$$

The distribution of the EM lifetimes are shown in Fig. 6, together with the experimental results obtained from Filippi *et al.* [4]. The lognormal mean and standard deviation of the simulated lifetimes are $\bar{t_f} = 17.5$ h and $\sigma_{t_f} = 0.41$, respectively. We can see that the simulation results provide a reasonable description for the early EM lifetimes.

A major advantage of (10) is that it forms a simple analytical model which is more rigorously related to the physical mechanisms active during the early EM failure development than Black's equation. A critical issue arises, however, with regard to the estimation of the parameter a. This parameter is affected by several factors, like diffusion coefficients, mechanical moduli, microstructure, etc, so that it cannot be defined in a closed form based on (2)–(4). Nevertheless, we have observed that it can be related to Korhonen's solution. In this way, it can be directly described by an analytical expression and connected to physical parameters according to (5).

The relative difference between the simulated and experimental lifetimes for the same failure percentile varies between 15% and 20%, as shown in Fig. 7. The difference is smaller for shorter lifetimes, since the proposed slit void growth model is more accurate for very early failures, where the void volumes are smaller. Such an error magnitude is reasonable, given the required assumptions for the parameters and considering the simplicity of the model.

IV. CONCLUSION

A compact model for estimation of the early EM lifetimes in M1/via structures of copper dual-damascene interconnects was developed. The model was derived through the combination of a complete model for void nucleation together with a simple slit void growth mechanism under the via. It is shown that the EM stress build-up can be related to simple analytical solutions of the EM problem, which yields a convenient compact description for the void nucleation time and, moreover, for the early EM lifetime. Given the simplifications and assumptions made for the simulations, a reasonable approximation to experimental early EM failures has been obtained. As the model is more rigorously based on the relevant physical effects for the early EM failure development, taking into account the kinetics of void nucleation and growth, it provides a better description of the early EM lifetimes and also a more precise extrapolation of accelerated test results to use conditions than Black's equation.

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REFERENCES

[1] J. P. Gambino, T. C.Lee, F. Chen, and T. D. Sullivan, "Reliability Challenges for Advanced Copper Interconnects: Electromigration and Time-Dependent Dielectric Breakdown (TDDB)," *Proc. Intl. Symp. on the Physical and Failure Analysis of Integrated Circuits*, pp. 677–684, 2009.

[2] M. Gall, C. Capasso, D. Jawarani, R. Hernandez, H. Kawasaki, and P. S. Ho, "Statistical Analysis of Early Failures in Electromigration," *J. Appl. Phys.*, vol. 90, no. 2, pp. 732–740, 2001.

[3] A. S. Oates and M. H. Lin, "Electromigration Failure Distribution of Cu/Low-k Dual-Damascene Vias: Impact of the Critical Current Density and a New Reliability Extrapolation Methodology," *IEEE Trans. Device Mater. Rel.*, vol. 9, no. 2, pp. 244–254, 2009.

[4] R. G. Filippi, P.-C. Wang, A. Brendler, P. S. McLaughlin, J. Poulin, B. Redder, and J. R. Lloyd, "The Effect of a Threshold Failure Time and Bimodal Behavior on the Electromigration Lifetime of Copper Interconnects," *Proc. Intl. Reliability Physics Symp.*, pp. 444–451, 2009.

[5] J. R. Lloyd, "Electromigration Failure," *J. Appl. Phys.*, vol. 69, no. 11, pp. 7601–7604, 1991.

[6] M. E. Sarychev, Y. V. Zhitnikov, L. Borucki, C.-L. Liu, and T. M. Makhviladze, "General Model for Mechanical Stress Evolution During Electromigration," *J. Appl. Phys.*, vol. 86, no. 6, pp. 3068–3075, 1999.

[7] R. L. de Orio, "Electromigration Modeling and Simulation," Dissertation, Technische Universität Wien, 2010. [Online]. Available: http://www.iue.tuwien.ac.at/phd/orio/

[8] M. A. Korhonen, P. Borgesen, K. N. Tu, and C.-Y. Li, "Stress Evolution due to Electromigration in Confined Metal Lines," *J. Appl. Phys.*, vol. 73, no. 8, pp. 3790–3799, 1993.

[9] R. J. Gleixner, B. M. Clemens, and W. D. Nix, "Void Nucleation in Passivated Interconnect Lines: Effects of Site Geometries, Interfaces, and Interface Flaws," *J. Mater. Res.*, vol. 12, pp. 2081–2090, 1997.

[10] M. W. Lane, E. G. Liniger, and J. R. Lloyd, "Relationship Between Interfacial Adhesion and Electromigration in Cu Metallization," *J. Appl. Phys.*, vol. 93, no. 3, pp. 1417–1421, 2003.

[11] Z. S. Choi, R. Mönig, and C. V. Thompson, "Activation Energy and Prefactor for Surface Electromigration and Void Drift in Cu Interconnects," *J. Appl. Phys.*, vol. 102, p. 083509, 2007.

[12] R. Kirchheim, "Stress and Electromigration in Al-Lines of Integrated Circuits," *Acta Metall. Mater.*, vol. 40, no. 2, pp. 309–323, 1992.

[13] L. Doyen, X. Federspiel, L. Arnaud, F. Terrier, Y. Wouters, and V. Girault, "Electromigration Multistress Pattern Technique for Copper Drift Velocity and Black's Parameters Extraction," *Proc. Intl. Integrated Reliability Workshop*, pp. 74–78, 2007.