Compact Modeling of Interconnect Reliability

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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. In order to investigate the failure mechanisms, EM experiments are performed under accelerated conditions, where an interconnect line is stressed with a higher current density and at a higher temperature than those under typical use conditions. Then, for the estimation of the interconnect lifetime under a real operating condition the times to failure (TTF) obtained from the accelerated tests have to be extrapolated to the use current density and temperature. A correct description and an adequate extrapolation procedure are, therefore, a must for a correct reliability assessment regarding EM failures.

EM lifetimes are traditionally described by Black's equation [1]

$$t_{50} = A\frac{1}{j^n}\exp\left(\frac{E_a}{kT}\right), \tag{1}$$

where t_{50} is the mean time to failure, A is a constant, j is the electrical current density, n is a constant which describes the impact of the current density on the EM lifetime, E_a is the activation energy of the failure mechanism, k is Boltzmann's constant, and T is the temperature. The current density exponent is experimentally determined and normally lies in the range $1 \leq n \leq 2$. $n \sim 1$ indicates that the EM failure is mainly governed by the growth of a critical void which triggers the failure, while $n \sim 2$ implies that the EM failure is governed by the kinetics of void nucleation. If n is a fraction, it is assumed that both mechanisms contribute to the EM failure [2]. However, Lloyd [3] has argued that Eq. (1) is only correct, if n is exactly 1 or 2.

A further issue arises due to the bimodal character of EM failures in copper dual-damascene interconnects, where a late and an early failure mode have been observed [4]. Filippi *et al.* [5] has shown that $n \sim 1$ for the late failures, while it is a fraction for the early mode. Consequently, although Black's equation can be used to describe the late mode, it is not applicable to the early failures. The problem is that interconnect reliability is primarily determined by the early failures, so it is crucial to develop a suitable model for early EM lifetimes.

We present a compact model for early EM lifetimes which accounts for both, the nucleation and the growth mechanism. Void nucleation is a consequence of the development of mechanical stress in the metal line caused by EM material transport. As soon as the mechanical stress reaches a sufficient magnitude, void nucleation occurs. Fig. 1 shows the stress build-up for several interconnect lines obtained from numerical simulations of a rather complex model [6]. The analysis of the stress curves indicates that the stress development can be separated into two parts: the first one follows a linear growth, while the second part exhibits a square root increase with time. This is shown in Fig. 2 for a typical stress curve. The linear stress increase was first explained by Kirchheim [7], while the square root stress increase was obtained by Korhonen *et al.* [8].

Since a large stress is required to trigger void formation, the void nucleation time is primarily determined by the square root model $\sigma(t) = a\sqrt{t}$, where a is used as fitting parameter. By fitting the stress curves of the simulated lines the statistical distribution of a is determined, as shown in Fig. 3. Thus, the distribution of the time for void nucleation, shown in Fig. 4, is readily obtained from the above equation. These results demonstrate that mechanical stress build-up due to EM can be conveniently described by simple analytical expressions, in such a way that the time for void nucleation is readily obtained. Furthermore, the expressions can be directly related to the available solutions of Kirchheim [7] and Korhonen *et al.* [8].

Once a void is formed, it grows until the line fails due to a significant resistance increase. In the early failure mode a slit void under the cathode via is typically observed [9]. Therefore, a simple void growth model can be applied, as depicted in Figure 5, where the growth time is given by [10]

$$t_g = \frac{kTL_{via}}{eZ^*\rho jD_s}. \tag{2}$$

L_{via} is the via diameter, e is the elementary charge, Z^* is the effective charge, ρ is the metal resistivity, and D_s is the surface diffusivity. In this way, the contribution of the void growth mechanism, shown in Fig. 4, is also easily estimated.

The early EM lifetime is then the sum of the void formation time with the void growth time, given by

$$t_f = \left(\frac{\sigma_c}{a}\right)^2 + \frac{kTL_{via}}{eZ^*\rho jD_s}. \tag{3}$$

The distribution of the EM lifetimes is shown in Fig. 4, together with the experimental results obtained from Filippi *et al.* [5]. Although some difference can be seen, the model provides a reasonable approximation to the experimental ones.

To sum up, a compact model for estimation of the early EM lifetimes in copper dual-damascene interconnects has been presented. The model is based on the relevant physical effects

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of the early EM failure development, taking into account the kinetics of void nucleation and growth. Thus, 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.

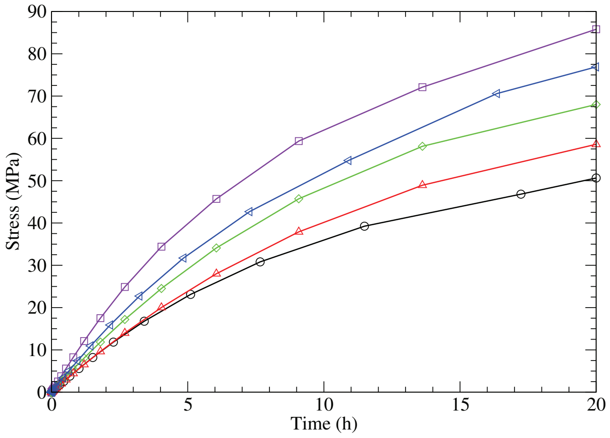

Fig. 1. Stress at the copper/capping/barrier layer intersection.

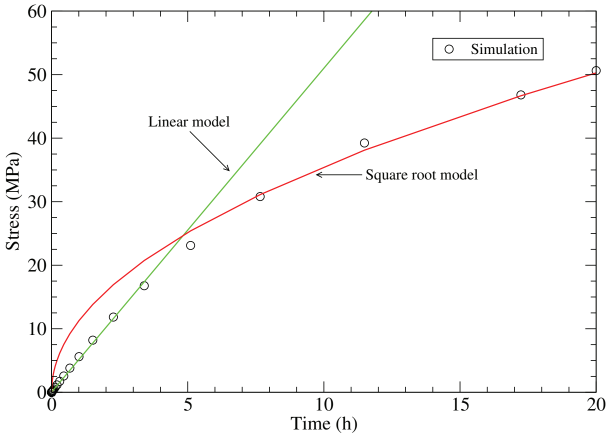

Fig. 2. Fitting of a numerical solution using a linear and a square root model.

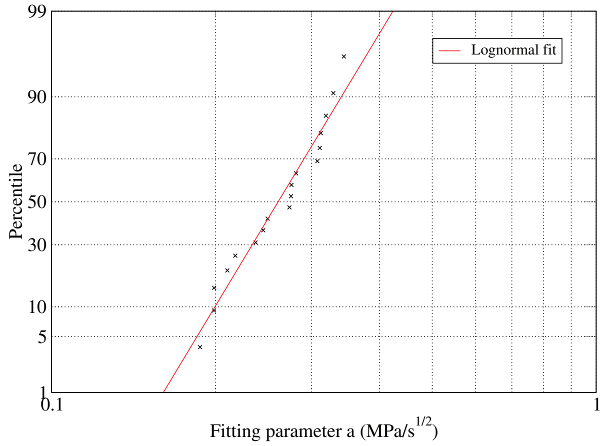

Fig. 3. Distribution of the square root model fitting parameter.

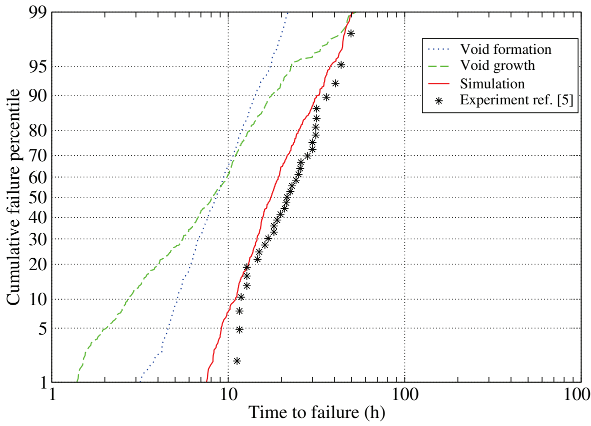

Fig. 4. Early EM lifetime distribution.

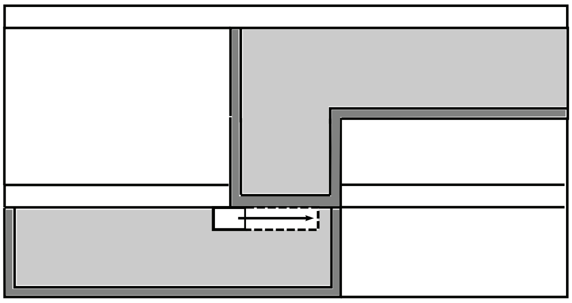

Fig. 5. Early failure mode: slit void growth under the via.

REFERENCES

[1] J. R. Black, "Mass Transport of Aluminum by Momentum Exchange with Conducting Electrons," *Proc. of 6th Annual Reliability Physics Symp.*, pp. 148–159, 1967.

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

[3] ——, "Black's Law Revisited – Nucleation and Growth in Electromigration Failure," *Microelectron. Reliab.*, vol. 47, pp. 1468–1472, 2007.

[4] 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.

[5] 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.

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

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

[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] 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.

[10] 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.