

Modeling Electromigration Lifetimes of Copper Interconnects

R. L. de Orio^{a,b}, H. Ceric^{a,b}, and S. Selberherr^a

^a Institute for Microelectronics, TU Wien, Gußhausstraße 27-29/E360, 1040 Wien, Austria

^b Christian Doppler Laboratory for Reliability Issues in Microelectronics

A model for early failure due to electromigration in copper dual-damascene interconnects is proposed. The model is based on analytical expressions obtained from solutions of electromigration stress build-up assuming slit void growth under the interconnect vias. It is demonstrated that the model satisfactorily describes the complex physics of void nucleation and growth of the electromigration damage. Furthermore, it is shown that the simulation results provide reasonable estimates for early electromigration failures.

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 h 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 proposed. 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 conveniently obtained. Moreover, it is shown that the simulation results provide a reasonable estimation for the lifetimes.

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 given by

$$t_f = t_n + t_g, \quad [1]$$

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.

Void Nucleation

Atomic transport due to EM in an interconnect line is accompanied by the production of mechanical stress according to the strain rate (6)

$$\frac{\partial \varepsilon}{\partial t} = \Omega \left[(1-f) \nabla \cdot \mathbf{J}_v + fG \right], \quad [2]$$

where Ω is the atomic volume, f is the vacancy relaxation ratio, and G is a source function. \mathbf{J}_v is the total vacancy flux given by

$$\mathbf{J}_v = -D_v \left(\nabla C_v + \frac{eZ^* \rho \mathbf{j}}{kT} C_v - \frac{Q^*}{kT^2} C_v \nabla T + \frac{f\Omega}{kT} C_v \nabla \sigma \right), \quad [3]$$

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, \mathbf{j} is the current density, Q^* is the heat of transport, σ is the hydrostatic stress, k is Boltzmann's constant, and T is the temperature.

In order to calculate the mechanical stress in a three-dimensional copper dual-damascene interconnect structure, Eq. [2] and Eq. [3] 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

$$\sigma(t) = \frac{2eZ^* \rho j}{\Omega} \sqrt{\frac{D_a B \Omega}{\pi k T}} t = a \sqrt{t}, \quad [4]$$

where D_a is the effective atomic diffusivity and B is the applicable modulus.

Void formation occurs as soon as the mechanical stress reaches a critical magnitude under the via edge at the cathode end of the line. Thus, the void nucleation time is determined by the condition $\sigma(t_n) = \sigma_c$, so that

$$t_n = \sigma_c^2 \frac{\pi k T \Omega}{(2eZ^* \rho j)^2 D_a B} = \left(\frac{\sigma_c}{a} \right)^2, \quad [5]$$

where σ_c is the critical stress.

The solution given by Eq. [4] is a good approximation to the more complete solution obtained by solving Eq. [2] and Eq. [3], 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.

Slit 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 Figure 1. Since the void is very thin and does not grow through the line height, its length is given by

$$l_{\text{void}} = v_d t, \quad [6]$$

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 Cu/barrier layer interface $D_{\text{Cu/barrier}}$, while the outgoing flux is governed by the surface diffusivity D_s . Since $D_s \gg D_{\text{Cu/barrier}}$, using the Nernst-Einstein equation one can write (9)

$$v_d = \frac{\delta_s}{h} \frac{eZ^* \rho j}{kT} D_s, \quad [7]$$

where δ_s is the thickness of the void surface and h is the line height. The EM failure occurs, when the void spans the via length L_{via} , so that the void growth time contribution to the EM lifetime is given by

$$t_g = \frac{L_{\text{via}}}{v_d} = \frac{h L_{\text{via}}}{\delta_s} \frac{kT}{eZ^* \rho j D_s}. \quad [8]$$

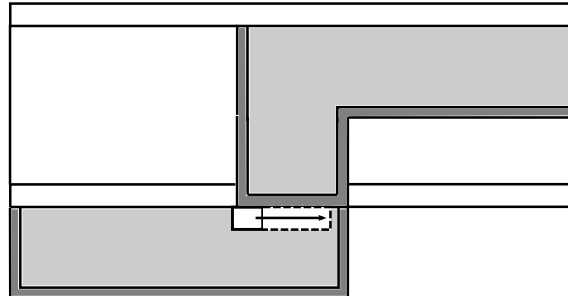


Figure 1. Early failure mode: slit void growth under the via.

Results and Discussion

Fully three-dimensional numerical simulations were carried out by solving Eq. [2] and Eq. [3] using an in-house finite element code (7). In order to obtain a statistical distribution of lifetimes a total of twenty lines containing different microstructures were simulated. The lines are assumed to have a “bamboo” grain structure.

Figure 2 shows the mechanical stress close to the via at the cathode end of a simulated line. The maximum stress is located at the intersection between a grain with the copper/barrier layer interface boundary at the via edge. This is the typical site for void formation and growth leading to early EM failures, as previously discussed. The stress development at such sites was monitored for all simulated lines, and the resulting stress build-up for five different structures is shown in Figure 3.

A careful analysis of the stress curves indicates that the stress development can be separated into two main parts: the first one corresponds to the lower stress magnitudes and follows a linear growth, while the second part exhibits higher stress magnitudes and a

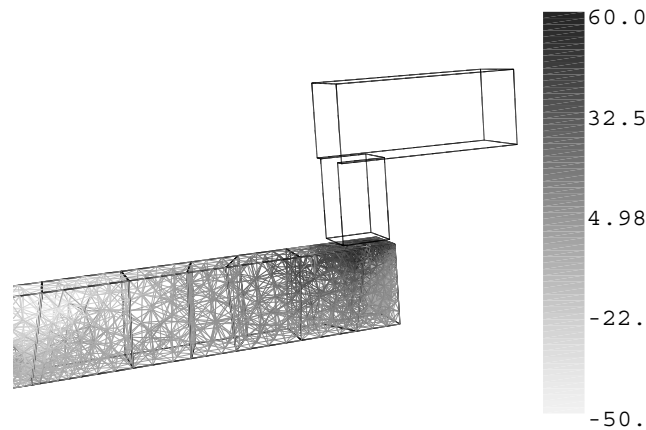


Figure 2. Hydrostatic stress distribution (in MPa). The maximum stress is located under the via.

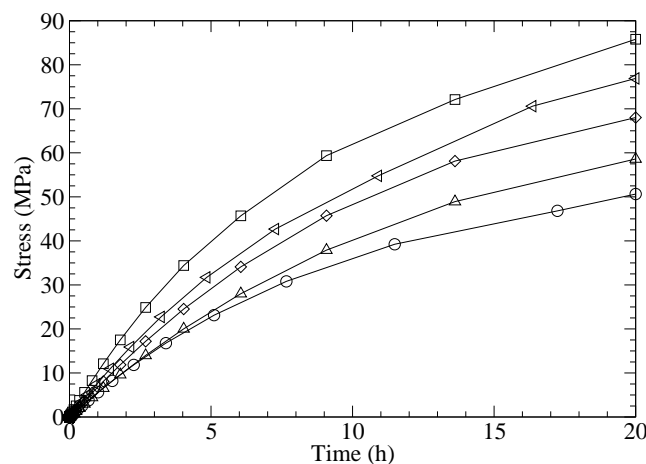


Figure 3. Maximum stress build-up under the via for lines with different microstructures.

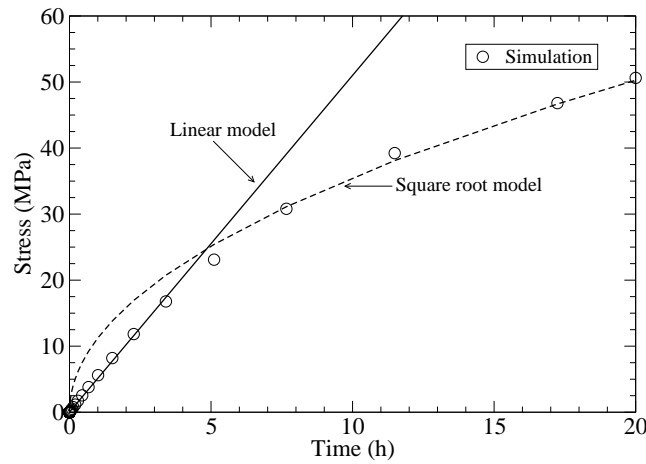


Figure 4. Fitting of a numerical solution using a linear and a square root model.

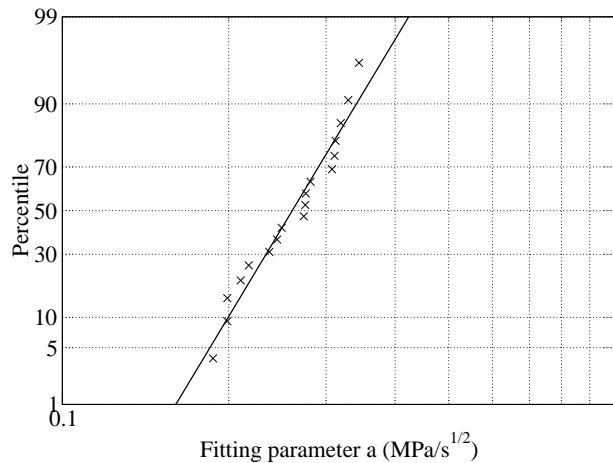


Figure 5. Distribution of the square root model fitting parameter.

square root increase with time. This is shown in Figure 4 for a typical stress curve. The portion of linear stress increase was first explained by Kirchheim (10) and the square root stress increase was obtained by Korhonen's solution, given in Eq. [4]. Thus, the stress increase at a grain boundary obtained from numerical simulations with a rather complete model and for fully three three-dimensional structures can be conveniently described by simple analytical solutions.

Since void nucleation is expected to occur at the higher stress magnitudes, the second part of the stress curve is fitted by the square root model given in Eq. [4], where a is a fitting parameter. By fitting the stress curves of all simulated structures, the distribution of the parameter a is determined, as shown in Figure 5. It is well described by lognormal statistics, where the mean and the standard deviation are $0.23 \text{ MPa/s}^{1/2}$ and 0.19 , respectively.

Applying Eq. [5] with the obtained parameter distribution, the distribution of times to void formation is readily obtained, as shown in Figure 6. Due to the lognormal statistics of a , the void formation time also follows a lognormal distribution, where the mean and standard deviation are 8.5 h and 0.38 , respectively.

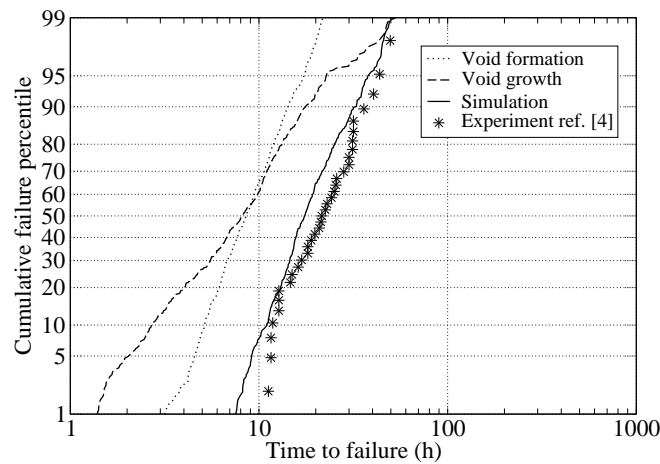


Figure 6. Early EM lifetime distribution.

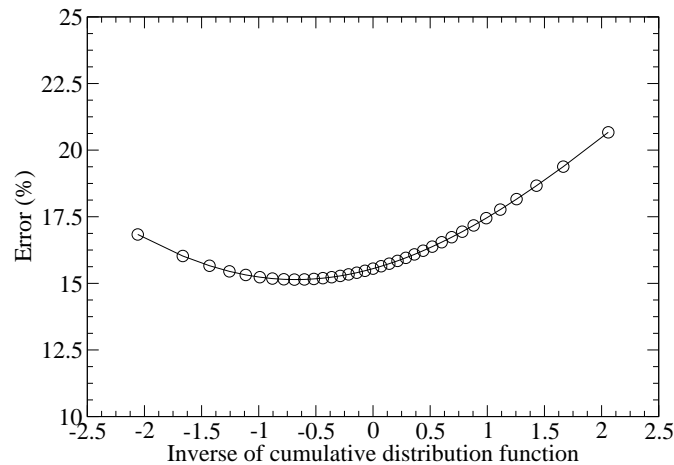


Figure 7. Error between the simulation and the experimental results.

The void growth time is determined by Eq. [8]. Choi *et al.* (9) obtained an activation energy for surface diffusivity of 0.45 ± 0.11 eV from EM tests carried out with clean copper surfaces. Thus, it is expected that their measurement delivers a more precise copper surface diffusivity than the typical ones performed on oxidized surfaces and, therefore, we have used their estimation for the activation energy in the simulations. Furthermore, we have assumed that the activation energy follows a normal distribution (11). This leads to a lognormal distribution for the surface diffusivity and, consequently, for the void growth time. The resulting distribution of the void growth time is shown in Figure 6. The mean and the standard deviation are 8.0 h and 0.7, respectively. It should be pointed out that the void formation time and the void growth time are of the same order of magnitude, which highlights the importance of considering both contributions.

The total early EM lifetime distribution, shown in Figure 6, is obtained by summing up the nucleation and growth contributions, where the lognormal mean and standard deviation are 17.5 h and 0.41, respectively. Figure 6 also shows the experimental results obtained from Filippi *et al.* (4).

The relative difference between the simulated and experimental lifetimes for the same failure percentile varies between 15 % and 20 %, as shown in Figure 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. This error magnitude is reasonable, considering the assumptions made for the model parameters and the simplicity of the model. Therefore, we can say that the simulation results provide satisfactory estimates for the early EM lifetimes.

Conclusion

A compact model for estimation of the early EM lifetime distribution of copper dual-damascene interconnects was developed. A key feature of the model is that it consists of a physical model based on simple analytical expressions, nevertheless providing a satisfactory description of the complex physics of EM phenomena in fully three-dimensional interconnects. The model accounts for both, the void formation and the void growth kinetics. Moreover, it can take into account the statistical distribution of physical parameters and is thus able to deliver a distribution of EM lifetimes. The simulations yield a reasonable estimation for the early EM lifetimes in comparison to published experimental results.

Acknowledgment

This work was supported in part by the Austrian Science Fund FWF, project P23296-N13.

References

1. J. P. Gambino, T. C. Lee, F. Chen, and T. D. Sullivan, *Proc. Intl. Symp. on the Physical and Failure Analysis of Integrated Circuits*, 677 (2009).
2. M. Gall, C. Capasso, D. Jawarani, R. Hernandez, H. Kawasaki, and P. S. Ho, *J. Appl. Phys.*, **90**, 732 (2001).
3. A. S. Oates and M. H. Lin, *IEEE Trans. Device Mater. Rel.*, **9**, 244 (2009).
4. R. G. Filippi, P. C. Wang, A. Brendler, P. S. McLaughlin, J. Poulin, B. Redder, J. R. Lloyd, and J. J. Demarest, *Proc. IEEE Intl. Reliability Physics Symp.*, 444 (2009).
5. J. R. Lloyd, *Microelectron. Reliab.*, **47**, 1468 (2007).
6. M. E. Sarychev, Y. V. Zhitnikov, L. Borucki, C.-L. Liu, and T. M. Makhviladze, *J. Appl. Phys.*, **86**, 3068 (1999).
7. R. L. de Orio, *Electromigration Modeling and Simulation*, Dissertation, Technische Universität Wien, 2010.
8. M. A. Korhonen, P. Borgesen, K. N. Tu, and C. Y. Li, *J. Appl. Phys.*, **73**, 3790 (1993).
9. Z. S. Choi, R. Monig, and C. V. Thompson, *J. Appl. Phys.*, **102**, 083509 (2007).
10. R. Kirchheim, *Acta Metall. Mater.*, **40**, 309 (1992).
11. L. Doyen, X. Federspiel, L. Arnaud, F. Terrier, Y. Wouters, and V. Girault, *Proc. Intl. Integrated Reliability Workshop*, 74 (2007).