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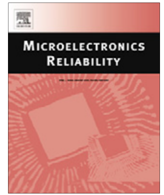

A compact model for early electromigration failures of copper dual-damascene interconnects

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ABSTRACT

A compact model for early electromigration failures in copper dual-damascene interconnects 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 electromigration lifetime is well described by a simple analytical expression, from where a statistical distribution can be conveniently obtained. Furthermore, it is shown that the simulation results provide a reasonable estimation for the lifetimes.

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1. 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 an interconnect structure [1]. Experimental works have observed several mechanisms of failure, and lately these mechanisms have been correlated to the statistical distribution of EM lifetimes [2]. This development has led to the explanation of the multimodal characteristic of the EM lifetime distribution. Consequently, the identification and separation of failure modes has provided a more complete understanding of the EM problem.

For copper dual-damascene interconnects two main EM failure modes have been identified, namely the late (strong) mode and the early (weak) mode [3]. The late failure mode is commonly characterized by the growth of a void which spans the line cross section. Here, the void grows by edge displacement in the direction of the electron flow, so that the line resistance gradually increases as the current has to flow through a larger portion of the liner. In turn, for a line/via structure subjected to downstream electron flow, the early failure mode is typically characterized by the growth of a slit void under the cathode via. Since the void is located in a critical position of the structure, a large and subtle resistance increase is normally observed [4].

These two failure mechanisms are considered to be the origin of the bimodal distribution observed in EM experiments. This means that the lifetime distribution 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 [5].

EM lifetimes are usually described by Black's equation [6]

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

where t_{50} is the mean time to failure, A is a constant, j is the current density, n is a current density exponent, E_a is the activation energy of the failure mechanism, k is Boltzmann's constant, and T is the temperature. The current density exponent normally lies in the range $1 \leqslant n \leqslant 2$, where $n \sim 1$ indicates that the EM failure is governed by the void growth mechanism [7] and $n \sim 2$ implies that the EM failure is mainly governed by the kinetics of void nucleation [8]. If n is a fraction, both mechanisms contribute to the EM failure. However, Lloyd [9] has argued that Eq. (1) is, in general, incorrect and it should be only applicable when n equals 1 or 2. Thus, while Eq. (1) can be used to describe the late failures, it cannot be applied to the early ones.

A typical reliability criterion allows one failure in 10^9 h of device operation [3]. 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 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 EM lifetime is obtained. It is shown that the simulations provide a reasonable estimation for the lifetimes.

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2. 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

$$t_f = t_n + t_g, \tag{2}$$

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 [7]. Therefore, modeling EM lifetimes requires the understanding of both phases of failure development.

2.1. 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

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

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, $\vec{j}$ is the current density, Q^* is the heat of transport, f is the vacancy relaxation ratio, Ω is the atomic volume, and σ is the hydrostatic stress.

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

$$\frac{\partial C_v}{\partial t} = -\nabla\cdot\vec{J}_v + G, \tag{4}$$

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 [10]

$$\frac{\partial\varepsilon}{\partial t} = \Omega\left[(1-f)\nabla\cdot\vec{J}_v + fG\right], \tag{5}$$

where ε is the trace of the strain tensor. Thus, Eq. (5) connects EM and mechanics. Since Cu dual-damascene interconnect lines are confined by surrounding layers, mechanical stress develops.

Using Einstein's summation notation the mechanical problem is given by the equilibrium equations [11]

$$\frac{\partial\sigma_{ji}}{\partial x_j} = 0, \quad i,j = 1,2,3 \tag{6}$$

together with the small displacement approximation for line deformation,

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \quad i,j = 1,2,3 \tag{7}$$

and the constitutive equation

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl}, \tag{8}$$

where an elastic deformation of the metal is assumed. σ_{ij} and ε_{ij} are the stress and strain tensor, respectively, and C_{ijkl} is the stiffness tensor.

The system of equations given by Eqs. (3)–(8) forms a general model for EM, whose solution yields the mechanical stress build-up for fully three-dimensional interconnect structures. Void formation occurs as soon as the mechanical stress reaches a critical magnitude at a site of weak adhesion, typically at the Cu/capping layer interface [12,13]. Thus, the void nucleation time is determined by the condition

$$\sigma(t_n) = \sigma_c, \tag{9}$$

where σ_c is the critical stress.

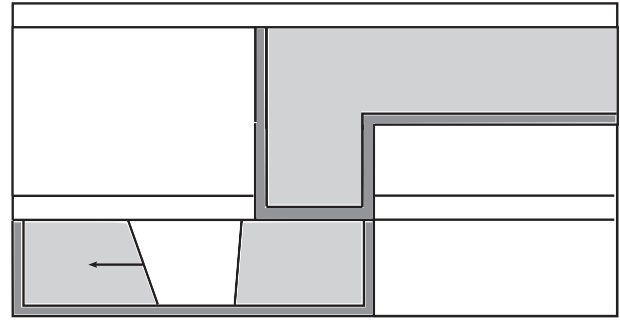

Fig. 1. Late failure mode: trench void growth.

2.2. Void growth

The growth of fatal voids is the ultimate cause for EM induced interconnect failures. It can encompass several development phases before it definitely triggers the failure [14]. For a copper dual-damascene M1/via structure with downstream electron flow, EM failure analyses [4] have identified two main types of fatal voids: trench voids spanning the line cross section, depicted in Fig. 1, and slit voids located under the via, shown in Fig. 2. As already mentioned, these two types of voids are associated with the late and the early failure mode, respectively.

For a trench void to cause a failure, it first has to span the line cross section and then grow along the line. Therefore, this type of void has to be described by a three-dimensional growth process. In this work, we focus on the early failure mode, which is normally characterized by a slit void formed under the via, as shown in Fig. 2. Here, the void is very thin and does not grow through the line height. Thus, the slit void growth can be described by a one-dimensional process, so that the void length is given by

$$l_{void} = v_d t, \tag{10}$$

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 $D_{\mathrm{Cu/barrier}}$, while the outgoing flux is governed by the surface diffusivity D_s. Since $D_s \gg D_{\mathrm{Cu/barrier}}$, using the Nernst–Einstein equation one can write [15]

$$v_d = \frac{eZ^*\rho j}{kT}D_s. \tag{11}$$

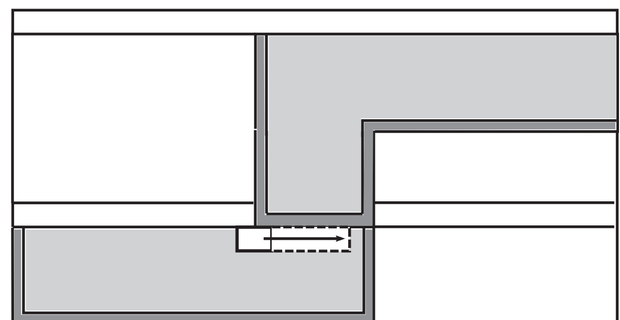

Fig. 2. Early failure mode: slit void growth under the via.

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

$$t_g = \frac{L_{via}}{v_d} = \frac{kTL_{via}}{eZ^* \rho j D_s}. \quad (12)$$

3. Results

Fully three-dimensional numerical simulations were carried out by solving Eqs. (3)–(8) 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 elsewhere [16].

In order to obtain a statistical distribution of lifetimes several lines containing different microstructures were simulated. A microstructure is generated by cutting an interconnect line along its length by planes which form the grain boundaries. In this way, the lines are assumed to have a "bamboo" grain structure. The size of the grains is determined from a lognormal distribution obtained for a given mean grain size and standard deviation. The lognormal distribution is used, because it has been observed that the sizes of copper grains in a typical dual-damascene process technology are well described by lognormal statistics [17].

The simulations are performed for a current density and temperature of 1.33 MA/cm^2 and 295 °C, respectively. Fig. 3 shows the mechanical stress close to the via at the cathode end of a simulated line. A high stress develops under and also 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. Therefore, we have assumed that the copper/capping/barrier layer intersection is a region of weak adhesion, where a void nucleates. The stress development at such sites was monitored for all simulated lines. The resulting stress build-up for five different structures is shown in Fig. 4.

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 square root increase with time. This is shown in Fig. 5 for a typical stress curve. The portion of linear stress increase was first explained by Kirchheim [18] and the square root stress increase was obtained by Korhonen et al. [19]. Thus, Fig. 5 shows that the stress build-up obtained from our numerical simulations with a rather complete model and for fully three three-dimensional structures can be conveniently related to simple analytical solutions.

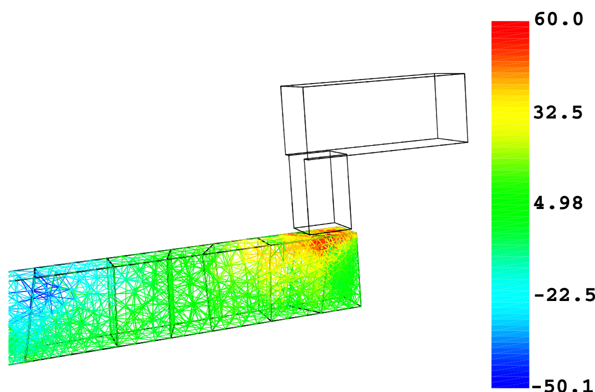

Fig. 3. Hydrostatic stress distribution (in MPa). A high stress develops at the copper/capping/barrier layer intersection adjacent to the via.

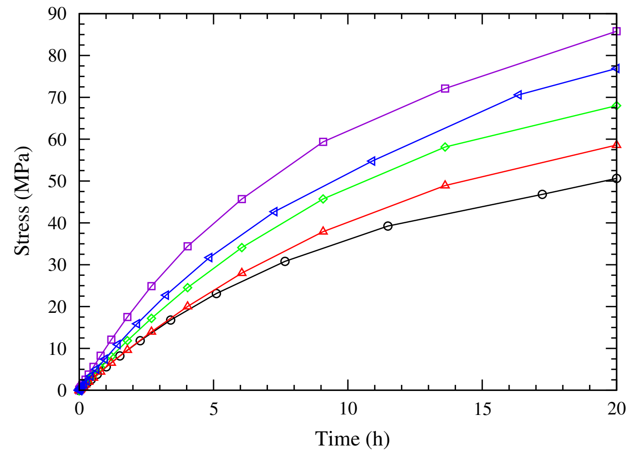

Fig. 4. Stress build-up at the copper/capping/barrier layer intersection for lines with different microstructures.

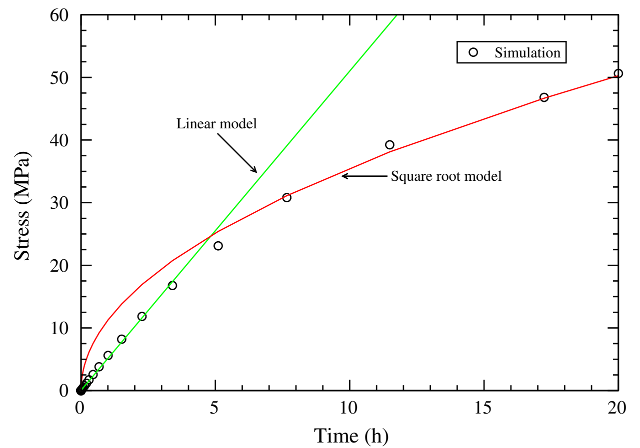

Fig. 5. Fitting of a numerical solution using a linear and a square root model.

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

$$\sigma(t) = a\sqrt{t}, \quad (13)$$

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. 6. 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.

Combining Eqs. (9) and (13) the void formation time is obtained from

$$t_n = \left(\frac{\sigma_c}{a}\right)^2. \quad (14)$$

Since the distribution of a is known, the statistical distribution of the void formation times is obtained, as shown in Fig. 7. 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 $\sigma_{t_n} = 0.38$.

The void growth time is determined by Eq. (12), where the normally distributed [20] activation energy for surface diffusivity is 0.45 ± 0.11 eV [15]. Consequently, the void growth time follows

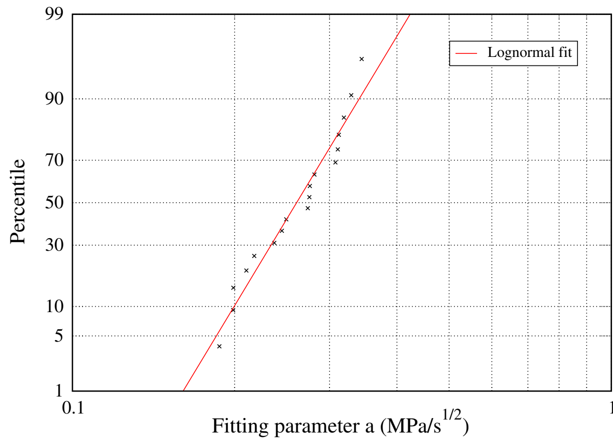

Fig. 6. Distribution of the square root model fitting parameter.

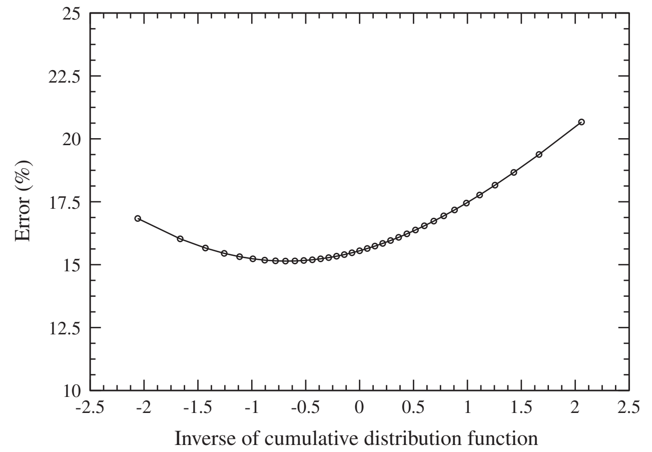

Fig. 8. Error between the simulation and the experimental results.

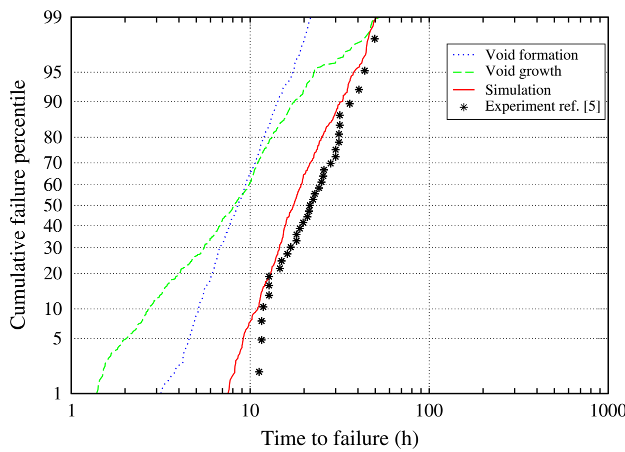

Fig. 7. Early EM lifetime distribution.

the lognormal statistics, where the mean and the standard deviation are $\bar{t_g} = 8.0$ h and $\sigma_{t_g} = 0.7$, respectively.

The total early EM lifetime, shown in Fig. 7, is then obtained from the nucleation and growth contributions, Eqs. (14) and (12), so that

$$t_f = \left(\frac{\sigma_c}{a}\right)^2 + \frac{kTL_{via}}{eZ^* \rho j D_s}. \quad (15)$$

The lognormal mean and standard deviation are $\bar{t_f} = 17.5$ h and $\sigma_{t_f} = 0.41$, respectively. The parameters used in the calculations are shown in Table 1. Fig. 7 also shows the experimental results obtained from Filippi et al. [5]. We can see that the simulation results provide a reasonable description for the early EM lifetimes.

The relative difference between the simulated and experimental lifetimes for the same failure percentile varies between 15% and 20%, as shown in Fig. 8. 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.

Table 1
Parameters used in the simulation.

Parameter	Value	Reference
σ_c	41 MPa	[21]
D_{s0}	6.7×10^{-9} cm²/s	[15]
E_s	0.45 eV	[15]
L_{via}	0.07 μm	[5]
Z^*	5.0	[22]
ρ	2.5×10^{-8} Ω m	[23]
j	1.33 MA/cm²	[5]
T	295 °C	[5]

4. Discussion

The equation for EM lifetimes given in Eq. (15) forms a compact model for early failures in M1/via structures of copper dual-damascene interconnects. It was derived through the combination of a rather complete EM model for void nucleation together with a simple slit void growth model under the via. Thus, the model accounts for both the void nucleation and the void growth contribution to the total failure time.

The simulations indicates that the void formation time and the void growth time are of the same order of magnitude, as shown in Fig. 7. Particularly, the mean values of both distributions are very similar. These results highlight the importance of considering both contributions.

The void nucleation time is a function of the parameter *a*, which is determined from the numerical simulations. Filippi et al. [5] estimated a nucleation time of approximately 5 h, which lies within the range predicted by the simulations. In turn, the void growth time is determined by the surface diffusivity. Choi et al. [15] obtained the activation energy for surface diffusivity 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 [15] and, therefore, we have used their activation energy estimate in the simulations. Furthermore, we have assumed that the activation energy follows a normal distribution [20]. As a consequence, both the surface diffusivity and the void growth time are lognormally distributed.

The comparison between the simulated and the experimental lifetimes resulted in an error close to 15%. Such an error magnitude is reasonable, given the required assumptions for the model parameters and considering the simplicity of the model.

It should be pointed out that the simple analytical expression given by Eq. (15) is an important feature of our model. This is very convenient, since the model can be easily fitted to experiments. 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 Eqs. (3)–(8). We could overcome this inconvenience by performing numerical simulations. Nevertheless, we have observed that the stress build-up given by Eq. (13) has the same form as Korhonen's solution for a simplified model [19]. Thus, the fitting parameter *a* can be directly

correlated to physical parameters via Korhonen's solution, so that the compact model given in Eq. (15) can then be re-written as

$$t_f = \frac{\pi}{4} \frac{\Omega kT}{(eZ^* \rho j)^2 BD_a} \sigma_c^2 + \frac{kTL_{via}}{eZ^* \rho j D_s}, \quad (16)$$

where the connection between a and physical quantities becomes obvious. At first, this equation is equivalent to Eq. (15), however, its main advantage is that it can be directly fitted to experimental results.

5. Conclusion

A compact model for estimation of the early EM lifetimes in M1/via structures of copper dual-damascene interconnects was developed. Given the simplicity of the model, a reasonable description of the early EM failures was obtained. The model takes into account the kinetics of nucleation and growth, so it should provide 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.

Acknowledgment

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References

[1] Gambino JP, Lee TC, Chen F, Sullivan TD. In: Proc intl symp on the physical and failure analysis of integrated circuits; 2009. p. 677–84.
[2] Gignac LM, Hu C-K, Liniger EG. Microelectron Eng 2003;70:398–405.
[3] Gall M, Capasso C, Jawarani D, Hernandez R, Kawasaki H, Ho PS. J Appl Phys 2001;90:732–40.
[4] Oates AS, Lin MH. IEEE Trans Device Mater Reliab 2009;9:244–54.
[5] Filippi RG, Wang P-C, Brendler A, McLaughlin PS, Poulin J, Redder B, et al. In: Proc Intl Reliability Physics Symp; 2009. p. 444–51.
[6] Black JR. In: Proc of 6th annual reliability physics symp; 1967. p. 148–59.
[7] Lloyd JR. J Appl Phys 1991;69:7601–4.
[8] Shatzkes M, Lloyd J. J Appl Phys. 1986;59:3890–3.
[9] Lloyd JR. Microelectron Reliab 2007;47:1468–72.
[10] Sarychev ME, Zhitnikov YV, Borucki L, Liu C-L, Makhviladze TM. J Appl Phys 1999;86:3068–75.
[11] Zienkiewicz OC, Taylor RL. The finite element method for solid and structural mechanics. Elsevier Butterworth Heinemann; 2005.
[12] Gleixner RJ, Clemens BM, Nix WD. J Mater Res 1997;12:2081–90.
[13] Lane MW, Liniger EG, Lloyd JR. J Appl Phys 2003;93:1417–21.
[14] Choi ZS, Mönig R, Thompson CV. J Mater Res 2008;23:383–91.
[15] Choi ZS, Mönig R, Thompson CV. J Appl Phys 2007;102:083509.
[16] de Orio RL. Electromigration modeling and simulation, Dissertation, Technische Universität Wien; 2010.
[17] Hauschildt M. Statistical analysis of electromigration lifetimes and void evolution in Cu interconnects, Dissertation, The University of Texas at Austin; 2005.
[18] Kirchheim R. Acta Metall Mater 1992;40:309–23.
[19] Korhonen MA, Borgesen P, Tu KN, Li C-Y. J Appl Phys 1993;73:3790–9.
[20] Doyen L, Federspiel X, Arnaud L, Terrier F, Wouters Y, Girault V. In: Proc intl integrated reliability workshop; 2007. p. 74–8.
[21] Hau-Riege SP. J Appl Phys 2002;91:2014–22.
[22] Lodder A, Dekker JP. In: Proc of the stress induced phenomena in metallization: 4th international workshop, vol. 418; 1998. p. 315–29.
[23] Doyen L, Petitprez E, Waltz P, Federspiel X, Arnaud L, Wouters Y. J Appl Phys 2008;104:123521.