Physically Based Models of Electromigration

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Invited Paper

Interconnect lifetimes due to electromigration (EM) failures are traditionally described by a modified Black equation [1]

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

where t_f is the time to failure (TTF), A is a constant, j is the electrical current density, n is a fitting parameter which describes the impact of the current density, E_a is the fitted activation energy representing the failure mechanism, k is Boltzmann's constant, and T is the temperature. Originally, Black's derivation resulted in $n = 2$ [1]. However, this was the source of an extensive debate [2], until more physically sound models showed that $n = 2$ is associated with a failure dominated by the void nucleation time [3], while $n = 1$ implies a failure dominated by the void growth time [4].

Although EM itself is the process of mass transport caused by the momentum transfer between conducting electrons and metal atoms, it encompasses atomic/vacancy transport along the interconnect line due to a combination of several driving forces, described by [5]

$$\vec{J}_v = -D_v\left(\nabla C_v - \frac{|Z^*|e}{kT}C_v\vec{E} - \frac{Q^*}{kT^2}C_v\nabla T + \frac{f\Omega}{kT}C_v\nabla\sigma\right),$$
$$\frac{\partial C_v}{\partial t} = -\nabla\cdot\vec{J}_v + G, \tag{2}$$

where D_v is the vacancy diffusivity, C_v is the vacancy concentration, Z^* is the effective charge number, e is the elementary charge, $\vec{E}$ is the electric field, Q^* is the heat of transport, f is the vacancy relaxation factor, Ω is the atomic volume, σ is the hydrostatic stress, and G represents a generation or annihilation term.

Initially, the EM failure was believed to be caused by vacancy accumulation and coalescence at a blocking boundary forming a void in the line. In this context, the mechanical stress contribution is neglected and (2) can be analytically solved for a one-dimensional line with a blocking boundary condition [3], resulting in a vacancy concentration development as shown in Fig. 1. This solution has two critical issues: 1) the vacancy saturation value is remarkably small for forming a void and 2) the time to reach this saturation is in the order of minutes at most, which is too short compared to the typical lifetimes measured after several hours.

The above inconsistencies are resolved by considering the impact of mechanical stress on the failure mechanism. Blech [6] observed that EM transport is followed by the creation of mechanical stress, in such a way that a stress gradient along the line acts as a back flux which can eventually balance the EM transport. This is shown in Fig. 2. The connection between the EM transport and the mechanical stress development is given by [7]

$$\frac{\partial\varepsilon}{\partial t} = \Omega\left[(1-f)\,\nabla\cdot\vec{J}_v + fG\right], \tag{3}$$

where ε is the trace of the strain tensor. Fig. 3 shows that a large mechanical stress develops after several hours of EM transport.

Gleixner *et al.* [8] carried out an extensive analysis of the void formation mechanism and showed that the rate of void nucleation in bulk and also on interfaces is too low compared to the experimental observations. However, in the presence of a defect at the top interface between the metal and the capping layer, the barrier energy for void nucleation and growth vanishes, when the mechanical stress becomes larger than the threshold [8]

$$\sigma_{th} = \frac{2\gamma_s\sin\theta_c}{R_p}, \tag{4}$$

where γ_s is the surface free energy of the metal, θ_c is the equilibrium contact angle between the void and the interface, and R_p is radius of the flaw.

The development of fatal voids leading to a significant resistance increase or even completely severing the interconnect line is the ultimate cause for the EM induced failure. The void evolution phase can encompass several processes: a void can migrate along the interconnect, interact with the local microstructure and grow, or even heal, undergo shape changes, before it definitely triggers the interconnect failure. The normal velocity at any point on the void surface is given by [9]

$$v_n = -\nabla\cdot\vec{J}_s - j_{nv},$$
$$\vec{J}_s = -\frac{D_s\delta_s}{kT}\left(\nabla_s\mu_s + e|Z_s^*|\vec{E}_s\right), \tag{5}$$

where $\vec{J}_s$ is the volumetric flux along the surface, j_{nv} is a transfer flux between the void surface and its surroundings, D_s is the atomic diffusivity on the surface, δ_s is the surface thickness, $\nabla_s\mu_s$ is the gradient of chemical potential along the surface, and $\vec{E}_s$ is the electric field tangential to the void surface.

Void evolution due to EM represents a moving boundary problem. Analytical solutions can only describe the asymptotic behavior of the moving boundary, since the shape changes that the void experiences cannot be analytically resolved. Therefore, a more general treatment demands the application of numerical methods and special techniques for tracking the void. The sharp interface model is a numerical method based on the direct solution of (5). This method requires an explicit tracking of the void surface and, consequently, a continuous remeshing procedure [10]. However, as the void evolves this explicit tracking becomes very demanding. Therefore, it can be satisfactorily applied only for simple two-dimensional cases

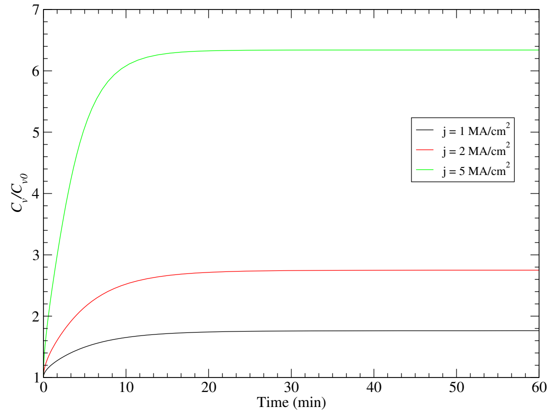

Fig. 1. Vacancy concentration as a function of time.

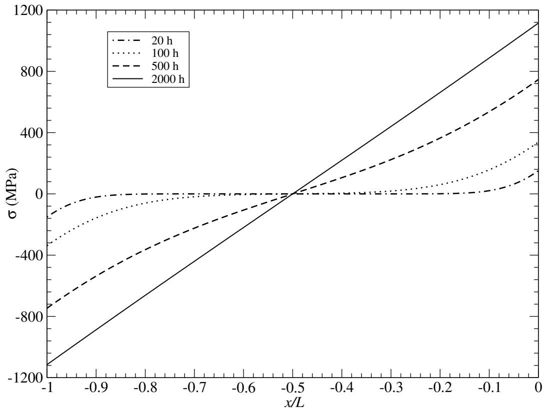

Fig. 2. Hydrostatic stress along a line.

and cannot be further extended. This shortcoming are overcome with the introduction of the so-called diffuse interface model [9]. The main advantage of this approach is that the void is implicitly represented by a field parameter, as shown in Fig. 4, so the demanding explicit void surface tracking can be avoided. Following Bhate *et al.* [9], the order parameter evolution is given by the equations

$$\frac{\partial \phi}{\partial t} = \frac{2D_s(\phi)}{\epsilon\pi}\nabla\cdot(\nabla\mu_s - e|Z_s^*|\nabla\varphi) - \frac{4}{\epsilon\pi}j_{nv},$$
$$\mu_s = 2\Omega\left[\frac{2\gamma_s}{\epsilon\pi}\left(f'(\phi) - \epsilon^2\Delta\phi\right) + \frac{\partial W}{\partial\phi}\right], \qquad (6)$$

where ϵ is a parameter that controls the thickness of the interface layer associated with void surface, $f(\phi)$ is the free energy of the homogeneous solid, and $W(\phi, \varepsilon)$ is the elastic strain energy.

In this paper we have presented the fundamental concepts of the EM modeling. In general, the numerical simulation of the EM failure development is a challenging task due to the wide diversity of concomitant physical effects influencing the EM transport. In addition, the need for special methods, mainly for the void evolution phase, makes fully three-dimensional simulations very demanding.

Acknowledgment

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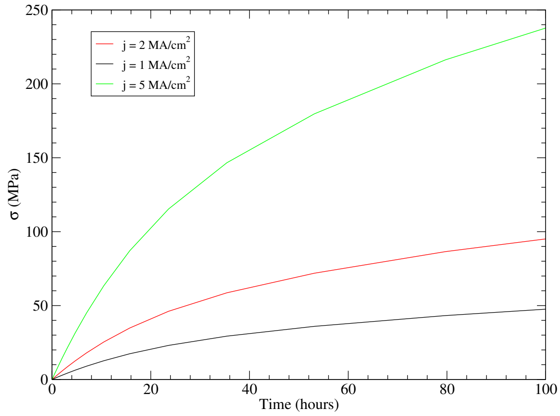

Fig. 3. Hydrostatic stress build-up as a function of time.

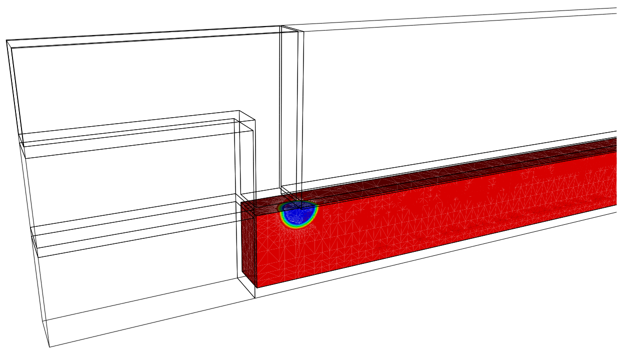

Fig. 4. Order parameter separating the bulk (red), the void (blue), and the diffuse interface region.

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