Electromigration instability: Transgranular slits in interconnects

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Evidence has recently accumulated that an interconnect under intense electric current can fail by a transgranular slit. A rounded void first forms, enlarges, and drifts. When the void becomes sufficiently large, a narrow slit emerges at the expense of the void, running across the linewidth. In this letter we describe a physical mechanism that explains this instability. Both electric current and surface energy drive atoms to diffuse on the void surface, but in the opposite directions. The slit emerges if the electric current prevails. An approximate analysis shows how the slit selects its width and velocity.

Aluminum lines in integrated circuits are subjected to intense electric current, and absolute temperature exceeding one third of the melting point. Electromigration along grain boundaries has long been held responsible for the failure.[1] However, as the linewidth falls below the grain size, the grain boundaries no longer connect into a continuous diffusion path. The aluminum lines are encapsulated by insulating layers, which eliminates the atomic sinks such as hillocks. These developments have raised new reliability issues. Among them are transgranular slits in fine lines observed experimentally in the last few years.[2-5] The phenomenon is not understood hitherto even qualitatively. In this letter we will describe a mechanism and estimate several important quantities.

Figure 1 illustrates a slit growing at the expense of a rounded void, as atoms diffuse on the internal surface, from the slit-tip toward the rounded void. For simplicity, it is assumed that the void is across the thickness h, and the conductor is isotropic. Both electric field and surface energy drive surface diffusion:

$$J = \frac{D_s \delta_s}{\Omega kT}\left(-eZ_s^* + \Omega \gamma_s \frac{d\kappa}{dl}\right). \tag{1}$$

Here J is the surface flux of atoms (the number of atoms passing per length per time), D_s the surface diffusivity, δ_s the thickness of the surface layer taking part in the diffusion process, Ω the atomic volume, k the Boltzmann constant, T the absolute temperature, Z_s^* (>0) the effective valence, e the magnitude of the electron charge, E_t the electric field projected on the surface, γ_s the surface energy, κ the curvature of the surface (positive for a rounded void), and l the arc length along the surface.

Physically, Eq. (1) says that atoms will diffuse in the direction of the electron flow if the field dominates, but toward the position with large curvature if the surface energy dominates. This competition between the electric field and the surface energy is essential for the slit-forming instability.

Subjected to an electric field, a circular void can translate in a conductor, without changing its shape, as atoms diffuse from one portion of the void surface to another. The moving circular void is a solution to Eq. (1); the surface energy does not drive diffusion in this situation, because the curvature is constant on the void surface.[6] However, the following consideration indicates that the circular void is unstable when the electric field is large. Suppose that a slit emerges at an acute angle from E_∞, the applied electric field. The field projected on the slit surfaces tends to move atoms away from the slit-tip and extend the slit. The surface energy has the opposite effect: It tends to move atoms toward the slit tip and heal the slit. A dimensionless number emerges from Eq. (1) and this consideration:

$$\chi = \frac{Z_s^* e E_\infty a^2}{\gamma_s \Omega}, \tag{2}$$

with a being the size of the rounded void. When χ is small, the surface energy dominates, and the void will remain rounded. When χ is large, the electric field dominates, and the slit will form. Similar dimensionless numbers appear in other electromigration instability phenomena, e.g., dislocation buckling,[7] cavity or precipitate penetrating a grain boundary.[8,9]

Next focus on the growing slit and answer the following question: How a slit selects its width and velocity. In Fig. 1, the electric field in the slit-wake drives the atoms away from the slit tip; the driving force scales as $Z_s^* e E_\infty$. On the other hand, the capillary force drives atoms toward the slit tip. Let $2u$ be the width of the slit. The curvature at the slit-tip is approximately $\kappa \approx 1/u$, and the curvature gradient $\approx 1/u^2$, so that the capillary force scales as $\gamma_s \Omega / u^2$. The dimensionless group

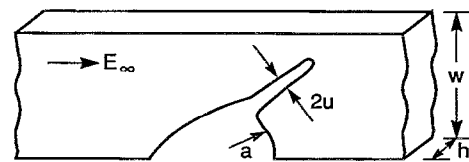$$\eta = \frac{Z_s^* e E_\infty u^2}{\gamma_s \Omega} \tag{3}$$

FIG. 1. A narrow slit emanates from a rounded void. The aluminum line is encased in an alumina scale or other insulating layers.
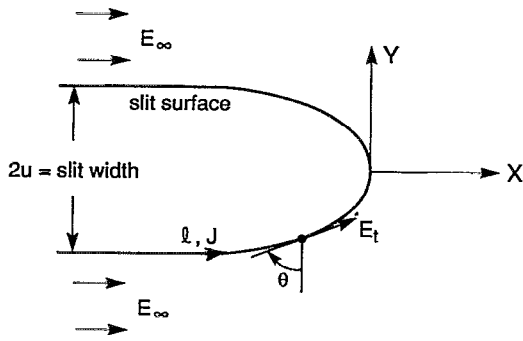
FIG. 2. A semi-infinite slit extending in an infinite crystal.

FIG. 3. The numerical solutions of Eqs. (8) and (9).

measures the relative magnitude of the two forces. Note that this group is similar to Eq. (2). The value of η depends on model details, to be estimated below.

The electric potential field in the conductor is governed by the Laplace equation and changes with the void shape. This complicates the analysis. Current crowding amplifies the electric field and thereby changes numerical factors, but it is not the essential reason that the instability takes place. According to the above description, even if a void were filled with a conducting fluid that eliminated current crowding, a slit would still emerge under intense current. Keeping this in mind, we will make simplifications that play down the current crowding effect.

For a slit growing at an acute angle from the applied field in Fig. 1, the applied field is decomposed into components parallel and normal to the slit. The former is taken to be responsible for slit growth. Figure 2 illustrates the model to be analyzed. A semi-infinite slit extends in an infinite crystal, subjected to an electric field E_∞ parallel to the slit. The applied field E_∞ projected along the surface tangent is

$$E_t = E_\infty \sin \theta, \qquad (4)$$

where θ is the tangent angle. Equation (4) gives the exact field in Fig. 2 at two limits, $\theta = 0$ and $\theta = \pi/2$, and will be taken as an approximation along the entire slit surface. The fields in Figs. 1 and 2 differ in details from Eq. (4), but the feature essential to the instability is retained: In all three cases the electric fields tend to move atoms away from the slit tip.

The long slit will extend steadily. The front moves with an invariant shape and every point moves at the same velocity, denoted as V. Mass conservation requires that the increasing volume of the slit be equal to the volume of atoms diffusing out in the wake. Thus,

$$Vu = \frac{D_s \delta_s}{kT} \, eZ_s^* E_\infty. \qquad (5)$$

The right-hand side is the volume per time of atoms diffusing out in the wake, as given by Eq. (1), because no capillary force exists in the flat wake.

The slit shape is described by a function $X(Y)$, Fig. 2. Consider the motion of a surface segment between 0 and Y. The flux J is a function of Y, and by symmetry $J(0) = 0$. As
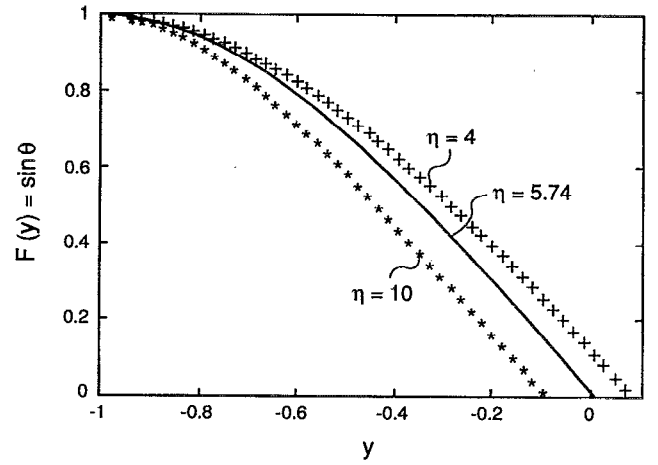
the segment translates at velocity V, the number of atoms removed per time per thickness is VY/Ω. Mass conservation requires that

$$J(Y) = YV/\Omega. \qquad (6)$$

When $Y = u$, Eqs. (6) and (1) reproduce Eq. (5).

The shape of the slit can be determined by an analysis similar to that of grain boundary cavities.[10] Denote $F = \sin \theta$; note that $dY/dl = \cos \theta$ and $\kappa = -d\theta/dl = -dF/dY$. The curvature gradient becomes

$$\frac{d\kappa}{dl} = \left(\frac{d\kappa}{dY} \right) \left(\frac{dY}{dl} \right)$$
$$= -\frac{d^2F}{dY^2} \cos \theta = -(1 - F^2)^{1/2} \frac{d^2F}{dY^2}. \qquad (7)$$

Substituting Eqs. (4)–(7) into Eq. (1), one obtains

$$\frac{1}{\eta} (1 - F^2)^{1/2} \frac{d^2F}{dy^2} + F + y = 0, \qquad -1 < y < 0, \qquad (8)$$

where $y = Y/u$. The vanishing slope and curvature in the wake give the initial conditions

$$F = 1, \quad dF/dy = 0, \quad \text{at } y = -1. \qquad (9)$$

The differential equation is solved using the fourth-order Runge–Kutta method; solutions for several values of η are plotted in Fig. 3. The condition that the tangent is vertical at the slit tip, $F(0) = 0$, selects the value $\eta = 5.74$.

Substituting $\eta = 5.74$ into Eqs. (3) and (5), one obtains

$$u = 2.40 (\Omega \gamma_s / Z_s^* e E_\infty)^{1/2}, \qquad (10)$$

$$V = 0.417 \frac{D_s \delta_s}{kT} \frac{(Z_s^* e E_\infty)^{3/2}}{(\Omega \gamma_s)^{1/2}}. \qquad (11)$$

For fixed material constants, the slit becomes narrower as the field increases, $w \propto E_\infty^{-1/2}$. Consequently, the narrow slits form only under high electric fields. Under $E_\infty = 540$ V/m, for aluminum with $\Omega = 1.66 \times 10^{-29}$ m^3, $\gamma_s = 1$ J/m^2, and

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$Z_s^* = 20$, the slit width predicted from Eq. (10) is $2u = 0.47$ μm. This is consistent in order of magnitude with the observed slit width.[2-4]

The aluminum lines under intense electric current fail by the transgranular slits, but the time spent from the slit emergence to the final failure is much shorter than the time spent to grow a rounded void to the critical size. Consequently, further attention should focus on the growth rate of the rounded void, and on the critical void size when a slit emerges. To reach estimates (10) and (11) in this first attempt, the effect of current crowding has been ignored. Further investigation taking this effect into account is in progress.

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