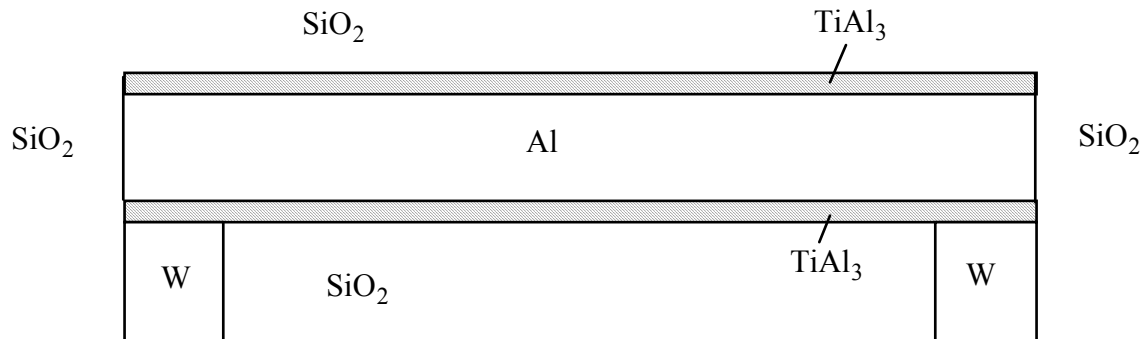


Lecture 12 Electromigration

This lecture is an abbreviated version of a section in the following article. A PDF file of the article is available online at www.deas.harvard.edu/suo, Publication 139.

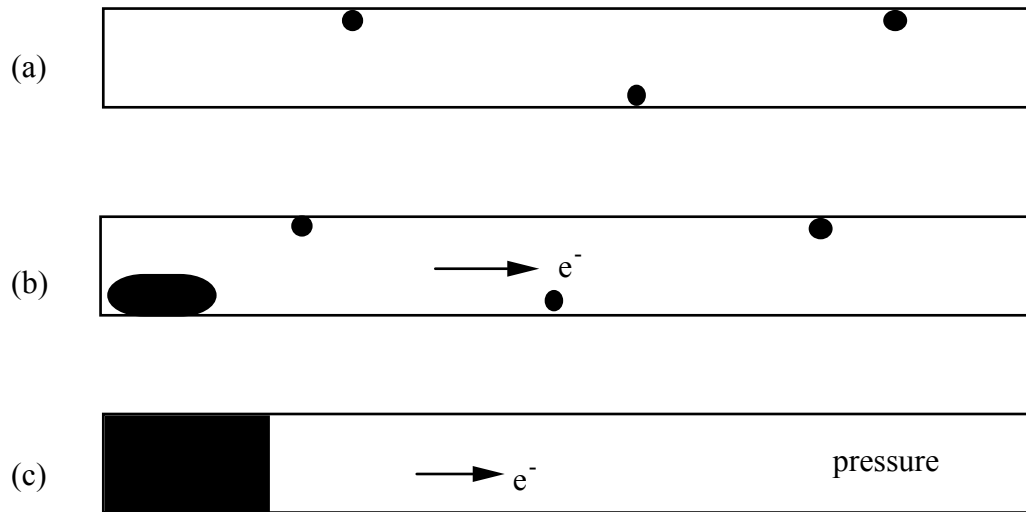
Z. Suo, Reliability of interconnect structures. pp. 265-324 in Volume 8: *Interfacial and Nanoscale Failure* (W. Gerberich, W. Yang, Editors), *Comprehensive Structural Integrity* (I. Milne, R.O. Ritchie, B. Karihaloo, Editors-in-Chief), Elsevier, Amsterdam, 2003.

Electromigration in interconnects. In service, an interconnect line carries an intense electric current. The conduction electrons impact metal atoms, and motivate the atoms to *diffuse* in the direction of electron flow. The process, known as electromigration, has been the most menacing and persistent threat to interconnect reliability.

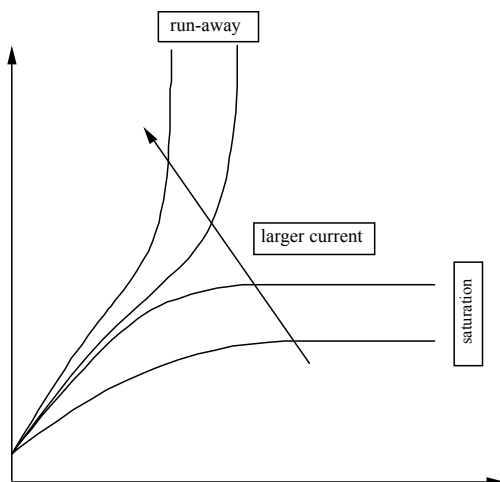


Consider an aluminum line encapsulated in a silica dielectric. The tungsten vias link aluminum lines between different levels. The titanium aluminide layers shunt the electric current where voids deplete a segment of aluminum. On cooling from the deposition temperature, thermal expansion misfit causes a tensile stress in aluminum. Voids may grow in the aluminum line. Each void relaxes the stress in its vicinity. After the line is subject to an electric current, the voids exhibit extraordinarily complex dynamics: they disappear, re-form, drift, change shape, coalesce, and break up. Despite the commotion in the transient, the end state is simple. After a sufficiently long time, the metal line reaches a steady state. Only a single void

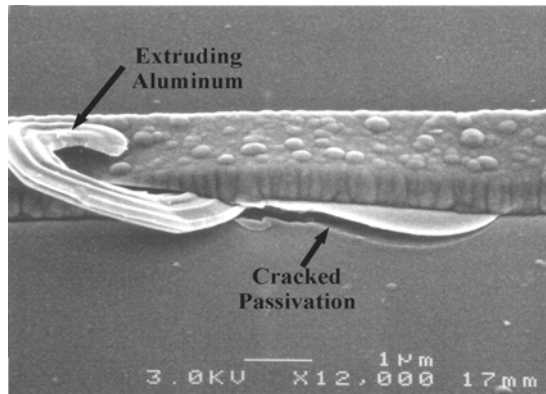
remains near the cathode; voids in the middle of the line have now been filled or swept into the cathode void. The total number of aluminum atoms is constant in the line. As the void at the cathode grows, atoms diffuse into the rest of the line, inducing a linear distribution of pressure. The pressure gradient balances the electron wind.



Imagine several identical lines, each carrying a different current. Consider the resistance change as a function of time. The resistance increases as the void enlarges. Two long-term trends are expected: the resistance either saturates or runs away. Evidently, the larger the



current, the higher the saturation resistance. For a line carrying a large current, a large pressure gradient is needed to stop mass diffusion. The high pressure in the metal near the anode, in its turn, may cause cracking or debonding in the encapsulation materials. Afterwards, the metal extrudes and the cathode void grows further, so that the resistance increases indefinitely.



Median-time-to-failure (MTF). Subject a batch of lines to a known current density and temperature. Due to the statistical nature of void formation, failure times scatter even for a batch of carefully processed lines. The MTF is taken as the time at which 50% of the lines have failed. In the

interconnect structure with shunt layers, voids never stop the current. A line is taken to have failed when the resistance increases by, say, 20%.

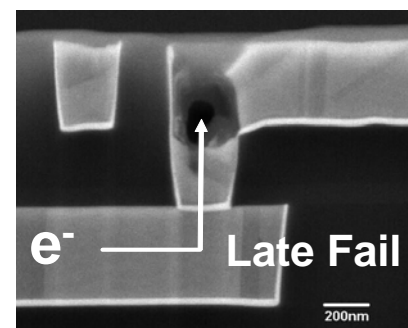
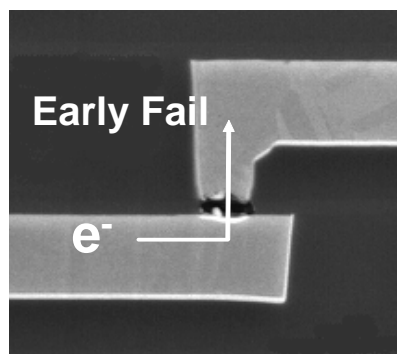
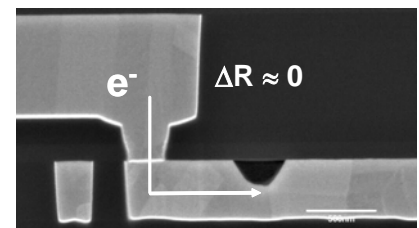
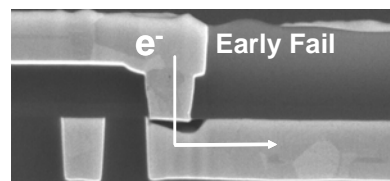
To fail lines within a time suitable for laboratory measurements, one has to accelerate the test by using temperatures and electric current densities higher than those used in service. The MTF can be measured for several temperatures and current densities. The results are fit to an empirical relation (Black, 1969):

$$\text{MTF} = A j^{-n} \exp\left(\frac{Q}{kT}\right),$$

where A , n and Q are fitting parameters. The exponent n typically ranges between 1 and 2. The activation energy Q determined this way is consistent with those determined by other methods.

The use of MTF to project service lifetime raises at least two objections. First,

the values of the MTF are measured under accelerated conditions. Any conclusion



drawn by extrapolation to the service condition is suspect. Second, the interconnect structure has little redundancy. The whole structure fails by the earliest failure of a small number of lines. Valid measurements of the low-percentage-failure tail of the time-to-failure curve involve large numbers of samples.

Electron wind. When a direct electric current flows in a metal, the moving electrons impart momentum to metal atoms. The electron wind force per atom, f_e , is proportional to the electric current density j . Write

$$f_e = Z^* e \rho j ,$$

where e is the electronic charge, and ρ the resistivity of the metal. Recall that ρj is the electric field in the metal line, and $e \rho j$ has the dimension of force. The dimensionless number Z^* is known as the effective charge number. The sign convention makes $Z^* < 0$, because the electron wind force is in the direction of the electron flow, opposite to that of the electric current density j .

The electron wind force is small. When an atom moves by an atomic distance b , the work done by the force, $f_e b$, is much below the average thermal energy kT . Taking representative values $b = 10^{-10}$ m, $Z^* = -2$, $\rho = 3 \times 10^{-8} \Omega\text{m}$, $j = 10^{10}$ A/m², we find that $f_e b = 5 \times 10^{-8}$ eV. The average thermal energy is $kT = 0.04$ eV at 500K. Recall that the energy barrier for atomic motion in metals is on the order of 1 eV. Consequently, the electron wind causes metal atoms to diffuse.

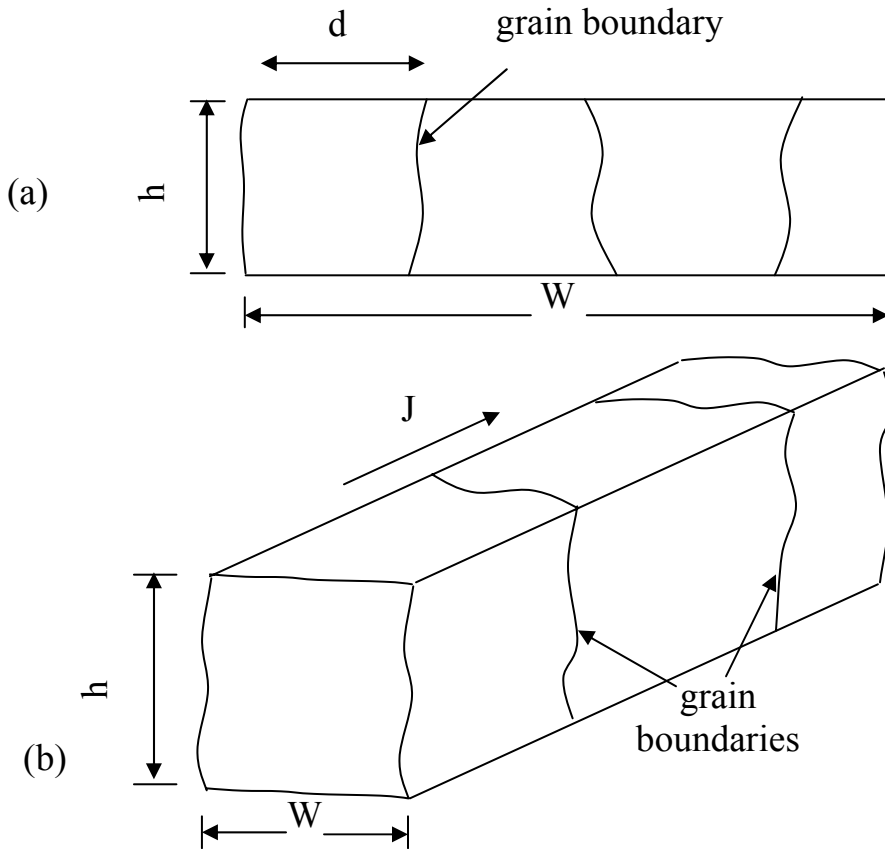
Atomic diffusion. Einstein's equation relates the atomic flux J (i.e., the number of atoms crossing unit area per unit time) to the electron wind force:

$$J = \frac{D Z^* e \rho j}{\Omega k T} ,$$

where $D = D_0 \exp(-Q/kT)$ is the diffusion coefficient, Q is the activation energy, and Ω is the volume per atom in the metal.

In a metal line, atoms may diffuse along several paths: the bulk crystal, the grain boundaries, the interface between the metal and the encapsulation, and the interface between the metal and the native oxide. The following figure sketches the cross-section of a wide metal line, width w and thickness h . The metal line has columnar grains of diameter d . The effective Z^*D results from all three kinds of paths:

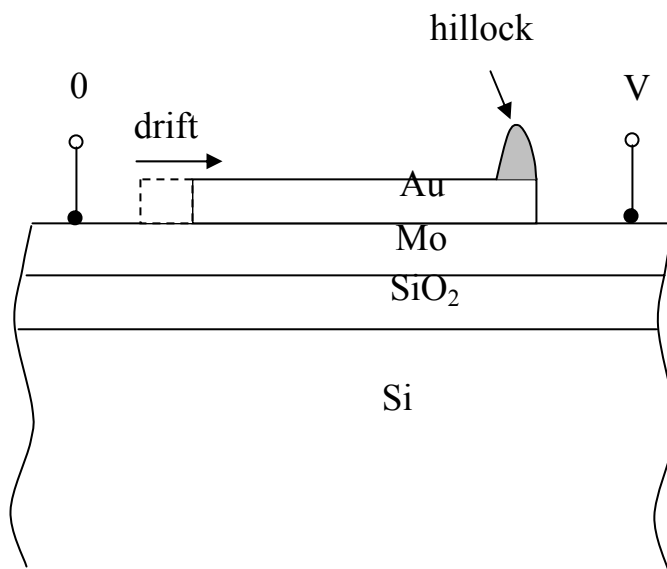
$$Z^*D = Z_B^*D_B + Z_G^*D_G\delta_G\frac{1}{d}\left(1 - \frac{d}{w}\right) + 2Z_I^*D_I\delta_I\left(\frac{1}{w} + \frac{1}{h}\right),$$



where the subscripts B , G , and I signify the bulk, the grain boundary, and the interface; δ_G and δ_I are the width of the grain boundary and the interface, respectively. The melting temperatures of aluminum and copper are 933K and 1358 K, respectively. The temperatures at which

electromigration is of concern are below 500 K. For fine metal lines, bulk diffusion is negligible. When a metal line is narrow, the grains form a bamboo structure, with all the grain boundaries perpendicular to the flux direction. For such a bamboo line, the grain boundaries do not contribute to the mass transport; the only remaining diffusion path is the interfaces. As miniaturization continues, a large fraction of atoms will be on the interfaces, so that the effective diffusivity will increase.

Line edge drift. Another useful experiment involves line edge drift. In their original experiment, Blech and Kinsbron (1975) deposited a gold film on a molybdenum film, which in turn was deposited on an oxide-covered silicon wafer. The molybdenum served as the electrodes. Because molybdenum has much higher resistance than gold, in the molybdenum/gold bilayer, the electric current mainly flew in gold. Gold atoms diffused in the direction of the electron flow. The edge of the gold film at the cathode drifted, and atoms piled up at anode edge. The edge of the gold film drifted at a constant velocity at a given current and temperature.



The drift velocity v relates to the atomic flux as $v = \Omega J$. One expresses the drift velocity as

$$v = \frac{DZ^* e \rho j}{kT}.$$

Rewrite the above equation as

$$\ln\left(\frac{vT}{j}\right) = \ln\left(\frac{D_0 Z^* e \rho}{k}\right) - \frac{Q}{kT}.$$

It is convenient to plot the experimentally measured $\ln(vT/j)$ as a function of $1/T$. The data points often fall on a straight line. The slope of the line determines the activation energy Q , and the intercept determines the product $D_0 Z^*$. An additional independent experiment is needed to separate D_0 and Z^* .

Compared to the MTF measurements, the drift velocity measurements require the observation of the edge displacement. In return, the drift velocity measurements provide the values of $D_0 Z^*$. Furthermore, the drift velocity does not have the large statistical scatter associated with void formation. In principle, a single sample can be used to measure the drift velocities at various temperatures. Such measurements are sufficient to determine Q and $D_0 Z^*$.

The drift experiment has been used to determine the dominant diffusion paths for aluminum and copper. It has been used to study alloying effects in copper lines. The drift experiment led Blech (1976) himself to discover a quantitative mechanical effect on electromigration. This landmark discovery has since become a guiding light in the interconnect structure design and electromigration research. The remainder of the section describes this discovery and its consequences.

Balancing electron wind with stress gradient. On measuring the drift velocity in an aluminum line, Blech (1976) found that the line edge drifted only when the current density was

above a threshold value. He tested lines between 30 and 150 μm long. The threshold current density was inversely proportional to the line length. The product of the line length L and the threshold current density j_c was a constant, $j_c L = 1.26 \times 10^5 \text{ A/m}$. The $j_c L$ product increased when the aluminum lines were encapsulated in silicon nitride. Blech attributed the observations to the pressure buildup near the anode. The pressure buildup in aluminum was evident as it sometimes cracked the overlying SiN. The pressure also caused a long aluminum extrusion through a hole etched in the SiN near the anode.

Blech used aluminum lines 25 μm wide and 0.46 μm thick, with columnar grains. Such wide films could develop biaxial stresses, but not triaxial stresses. Atoms left the cathode region, where tension arose. Atoms arrived in the anode region, where compression built up. At a point in the line, atoms diffuse along the grain boundaries to equalize the two inplane stress components. The inplane stresses could not be readily relaxed because diffusion on the aluminum-oxide interfaces is negligible. The stress gradient drove atoms to diffuse from the anode (in compression) to cathode (in tension). The direction was opposite to the electron wind. When the stress gradient balanced the electron wind, net atomic diffusion stopped.

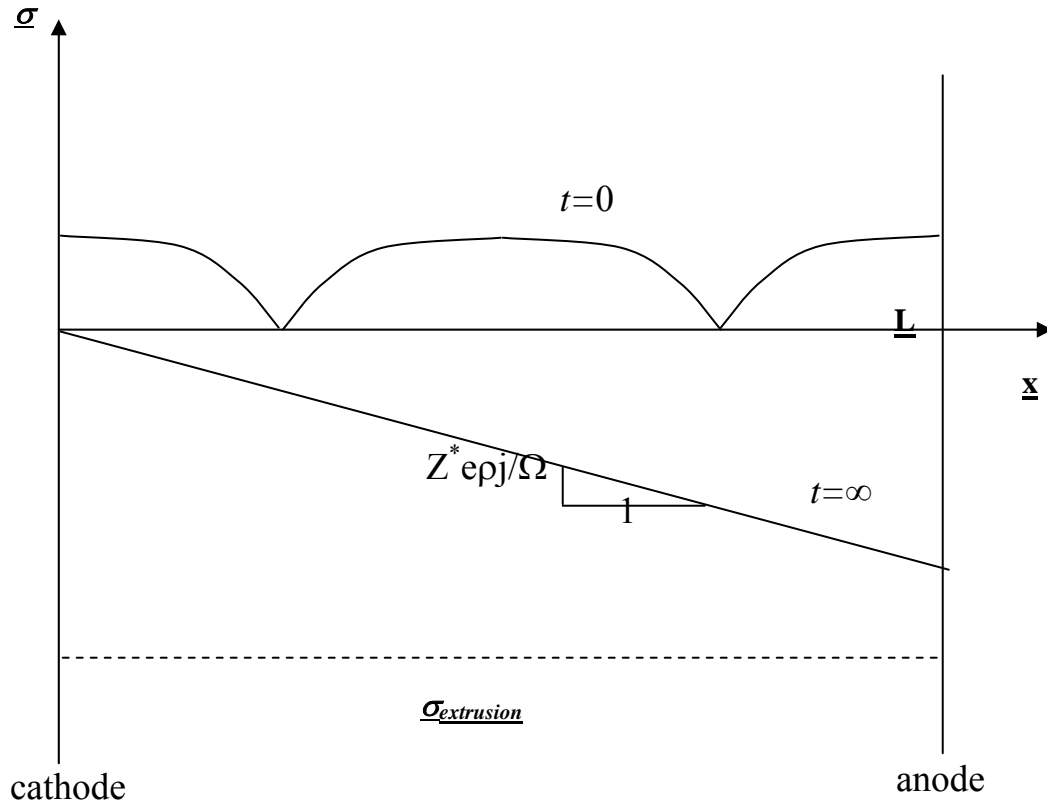
Denote the equal biaxial stress by σ , which is a function of the position x along the line and time t . An atom in the metal line is subject to both the electron wind and the stress gradient. The net force is the sum

$$f = Z^* e \rho j + \Omega \frac{\partial \sigma}{\partial x}.$$

The evolution of the stress field $\sigma(x, t)$ will be discussed later. We now focus on the steady state. After a sufficiently long time, the net atomic diffusion stops, and the net driving force vanishes, $f = 0$. The line reaches the steady state when the stress in the line has a constant slope, so that the stress needed to balance the electron wind force is

$$\Omega \Delta \sigma = Z^* e \rho j L,$$

where $\Delta \sigma$ is the stress difference between the two ends of the line. For a very small current, the steady stress $\Delta \sigma$ is small. Wide aluminum lines have finite yield strength, which has been determined by the wafer curvature measurements. The lines drift when the stresses at both ends exceed the yield strength. Take $\Omega = 1.66 \times 10^{-29} \text{ m}^3$, $Z^* = -2$, $\rho = 3 \times 10^{-8} \Omega \text{ m}$, $\Delta \sigma = 10^8 \text{ Pa}$, and we find that $j_c L = 1.73 \times 10^5 \text{ A/m}$.



Saturated void volume (SVV). A conservative model assumes that the voids grow in the metal line. Before the line carries the electric current, voids may already grow in the line due to thermal stresses. This stress distribution is labeled as $t = 0$ in the figure. After the line carries electric field for some time, all the voids along the line disappear, and a single void is left in the cathode edge. The void relieves the stress at the cathode, $\sigma(0, t) = 0$; the capillary pressure is

negligible. The stress at the anode becomes compressive. When the stress gradient balances the electron wind, the stress is linearly distributed along the line:

$$\sigma(x, \infty) = -Z^* e \rho j x / \Omega,$$

This stress distribution is labeled as $t = \infty$.

The void at the cathode end reaches the saturated volume. The thermal expansion mismatch contributes $3\Delta\alpha(T_0 - T)V$ to the SVV. The steady stress field σ contributes $A \int_0^L (\sigma / B) dx$ to the SVV, where A is the cross-sectional area of the metal line. Adding the two contributions, the SVV is

$$\frac{V_{sv}}{V} = 3\Delta\alpha(T_0 - T) + \frac{Z^* e \rho}{2\Omega B} jL.$$

The SVV increases when the temperature decreases and the current density increases. The void volume affects the resistance increase. Failure can be set to the condition that V_{sv} / V reaches a critical value. The slope of the line is proportional to B . Everything else being equal, $j_c L$ increases with B .

The copper interconnect structures in use today have very thin barrier layers. They are ineffective as shunts: the resistance abruptly increases when a void at the cathode grows across the via. A more appropriate failure criterion should be the void volume V_{sv} itself, rather than the volumetric strain V_{sv} / V , reaches a critical value. Neglecting the thermal strain, one finds that $V_{sv} \propto jL^2 / B$.

No-extrusion condition. In the steady-state with SVV, the compressive stress in the metal line at the anode is

$$\sigma_A = -Z^* e \rho j L / \Omega.$$

Using $L = 100 \text{ } \mu\text{m}$, $j = 1.0 \times 10^{10} \text{ A / m}^2$, $Z^* = 2$, $e = 1.6 \times 10^{-19} \text{ C}$, $\rho = 3 \times 10^{-8} \Omega\text{m}$, and $\Omega = 1.66 \times 10^{-29} \text{ m}^3$, one finds that the steady-state compressive stress at the anode is $\sigma_A = -600 \text{ MPa}$. The large stress may cause cracking or debonding of the encapsulation.

The fabrication process controls the geometry all the way to the feature size, so that crack-like flaws must be smaller than the feature size. Use the linewidth, w , as a representative size scale, the no-extrusion condition is stated as

$$\beta \frac{\sigma_A^2 w}{E} < \Gamma,$$

Here Γ is the fracture energy of an encapsulation material or an interface, E Young's modulus of a material, and β a dimensionless parameter depending on ratios of various elastic moduli and lengths that describe the anode. The values of β can be calculated by solving elasticity boundary value problems containing cracks. Taking representative values $\beta = 0.25$, $\Gamma = 4 \text{ J/m}^2$, $E = 70 \text{ GPa}$, and $w = 0.5 \text{ } \mu\text{m}$, one finds from (2) that the encapsulation can sustain anode pressure up to $|\sigma_A| = 1.5 \text{ GPa}$.

In the above, thermal stresses in the passivation have been ignored. Upon cooling from the processing temperature, a large compressive hoop stress arises in the oxide, resulting from the thermal expansion misfits between the aluminum and the oxide, and between the silicon substrate and the oxide. When an electric current is supplied, the volume of aluminum near the anode increases, which first compensates its thermal contraction, and then goes beyond. Consequently, in the stable state, the stress in the oxide is due to the pressure in the aluminum, and the thermal misfit between the oxide and the silicon substrate. The latter is negligible.

The immortal interconnect. Provided a circuit tolerates a variable resistance in an interconnect up to its saturation level, the interconnect is immortal. The interconnect evolves

into a stable state to adapt to newly established temperature and current. The immortality gives a simple perspective on reliability. One can focus on the stable state itself, rather than the transient process to reach it. The perspective plays down the roles of the time scale, the rate processes, and the microstructure of the metal. No longer need the microstructure be optimized for slow mass transport or low void nucleation rate. No longer need the median-time-to-failure (MTF) be measured, for the lifetime is infinite. No longer need a magic alloy be sought to slow down diffusion rate, for the diffusivity is irrelevant. In short, the reliability is warranted by energetics, rather than kinetics. Having thermodynamics on our side, the design is much more robust.

The use of the stable state is limited in two ways: the metal may extrude at the anode, or the saturation resistance may be prohibitively large. For a short line, the saturation void volume is small compared to the via size, giving rise to a small resistance change. Consequently, the stable state finds ready applications in short lines. The saturation void volume increases when the effective modulus B is small. The interconnect structure with low k dielectrics and thin barriers will no doubt require attention. The copper interconnect structures in use now have very thin barrier layers. They are ineffective as shunts: the resistance abruptly increases when a void at the cathode grows across the via.

Time evolution of stress and void in the electromigration test. We now discuss the model of Korhonen et al. (1993). The model formulates a partial differential equation for the stress in the interconnect, $\sigma(x, t)$. The atomic flux is due both to the electron wind and the stress gradient:

$$J = \frac{D}{\Omega kT} \left(Z^* e \rho j + \Omega \frac{\partial \sigma}{\partial x} \right). \quad (1)$$

A section of the interconnect loses atoms when the diffusion flux has a positive divergence. Let θ be the loss of volume per unit volume (i.e., the inelastic volumetric strain) of the interconnect.

Mass conservation requires that

$$\frac{\partial \theta}{\partial t} = \Omega \frac{\partial J}{\partial x}. \quad (2)$$

This inelastic volumetric strain induces the stress in the interconnect:

$$\sigma = B\theta, \quad (3)$$

where B is the effective elastic modulus.

A combination of the above equations gives

$$\frac{\partial \sigma}{\partial t} = \frac{DB\Omega}{kT} \frac{\partial^2 \sigma}{\partial x^2}. \quad (4)$$

This diffusion-like equation governs the stress $\sigma(x, t)$. The quantity $DB\Omega/kT$ serves the role of the diffusion constant. For an interconnect of length L , a time scale exists:

$$\tau = \frac{L^2 kT}{DB\Omega}. \quad (5)$$

We now consider a specific scenario. An interconnect, length L and cross-sectional area A is stress-free prior to the electromigration test, i.e., $\sigma(x, 0) = 0$ for $0 < x < L$. At the cathode, a void pre-exists, and the stress is taken to be zero at all time, $\sigma(0, t) = 0$. At the anode, the atomic flux vanishes, $J(L, t) = 0$, or $\frac{\partial \sigma}{\partial x}(L, t) = -\frac{Z^* e \rho j}{\Omega}$. These initial and boundary conditions, together with the partial differential equation (4), determine the stress in the interconnect, $\sigma(x, t)$. When the void at the cathode increases by volume ΔV , the atoms diffuse from the void surface into the interconnect. The volume gain per unit volume of the interconnect is $-\theta = -\sigma/B$, so that

$$\Delta V(t) = -A \int_0^L (\sigma/B) dx. \quad (6)$$

Depending on the value of t/τ , we can readily obtain two limiting solutions. When t/τ is small, the stress in the interconnect is negligible. Eq. (1) reduces to $J = DZ^*e\rho j/\Omega kT$. The cathode void volume grows as $\Delta V = \Omega J A t$, namely,

$$\Delta V = \frac{Z^*e\rho j D A t}{kT}. \quad (7)$$

If the failure time is reached when ΔV reaches a critical value, Eq. (7) reproduces Black's empirical relation: $t_f \propto j^{-1} \exp(Q/kT)$.

When t/τ is large, the interconnect approaches a steady state. The atomic diffusion flux vanishes, and the electron wind force balances the stress gradient, so that the stress is linearly distributed along the interconnect:

$$\sigma(x, \infty) = -\frac{Z^*e\rho j}{\Omega} x. \quad (8)$$

Inserting this stress distribution into Eq. (5), we obtain the saturation void volume:

$$\Delta V(\infty) = \frac{Z^*e\rho j L^2 A}{2\Omega B}. \quad (9)$$

For an immortal interconnect, the cathode void volume must be below a certain value at all time, so that jL^2/B must be below a critical value. We assume that all other quantities in Eq. (9) are constant.

In the transient state, the solution can be obtained by the method of separation of variable. The stress distribution takes the form

$$\sigma(x, t) = \frac{Z^*e\rho j L}{\Omega} f\left(\frac{x}{L}, \frac{tDB\Omega}{L^2 kT}\right). \quad (10)$$

Fig. 1 plots the dimensionless function f .

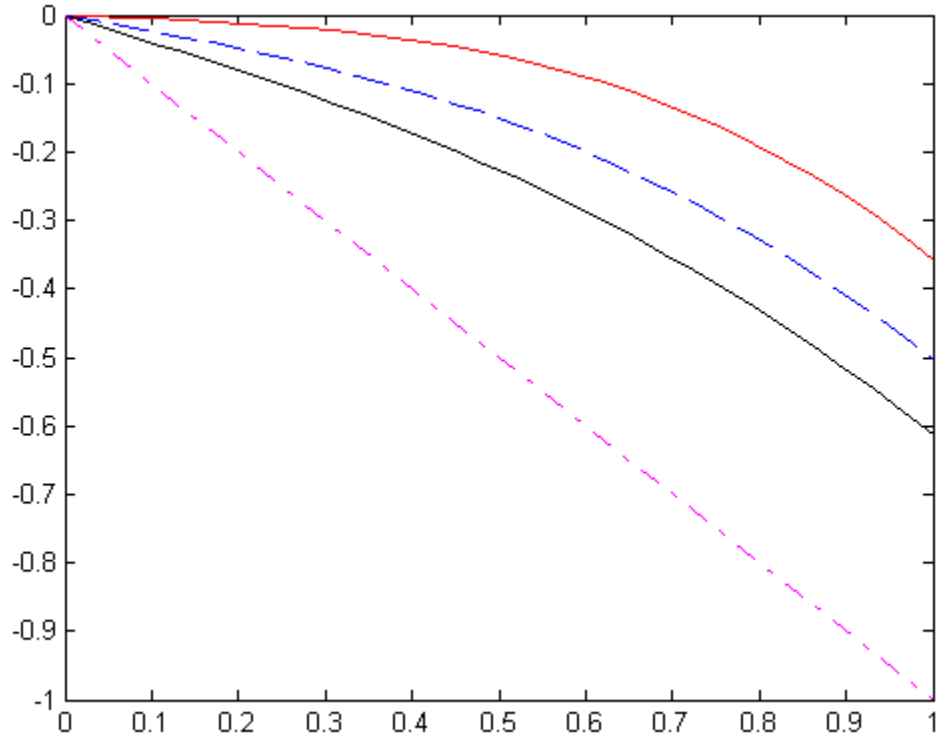


Figure 1 Stress $\sigma(x, t)$ versus x for $t = 0.1, 0.2, 0.3$, and ∞

The cathode void volume takes the form

$$\Delta V(t) = \frac{Z^* e \rho j L^2 A}{\Omega B} g\left(\frac{t D B \Omega}{L^2 k T}\right). \quad (11)$$

Fig. 2 plots the dimensionless function g . In the electromigration test, we may treat j, L, B as the control variables. The failure time is reached when the cathode void volume reaches a certain value. **Plot the experimental data $B / j L^2$ as a function of $t_f B / L^2$. It should look like Figure 2. (This statement has not been verified.)**

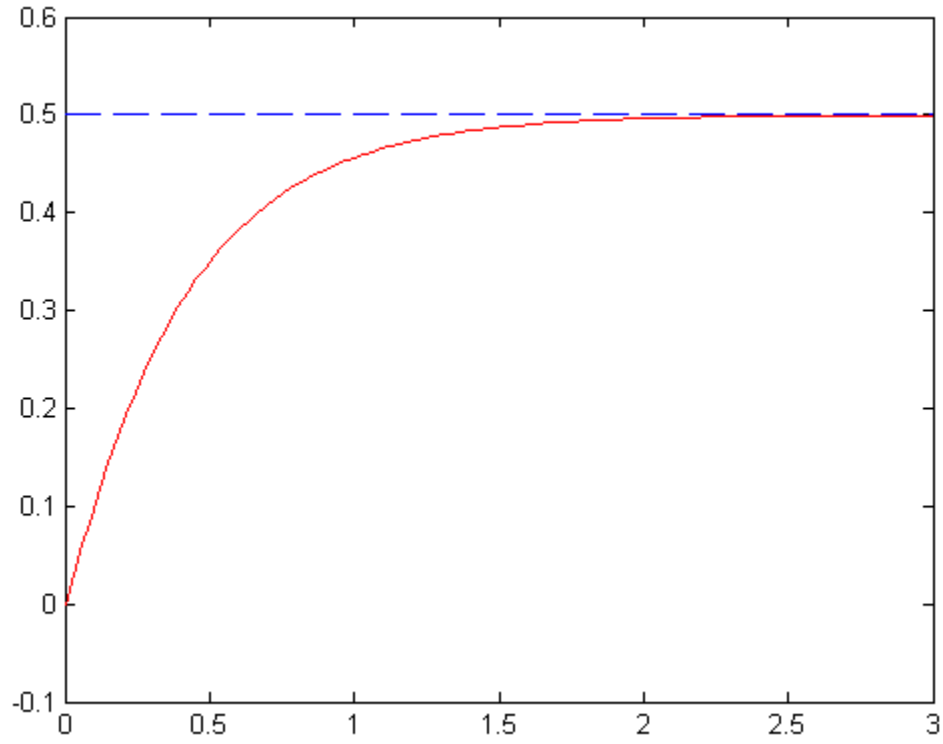


Figure 2. Void volume $V(t)$ versus t

We give the details of the initial-boundary value problem. In a dimensionless form, the governing equations are

$$\frac{\partial \sigma}{\partial t} = \frac{\partial^2 \sigma}{\partial x^2}$$

$$\sigma(x,0) = 0$$

$$\sigma(0,t) = 0$$

$$\frac{\partial \sigma}{\partial x}(1,t) = -1$$

The solution takes the form

$$\sigma(x,t) = -x + s(x,t).$$

The first term is the steady-state solution, and the second term describes the transient to reach the steady state solution. A separation of variable gives the form of the solution:

$$\sigma(x,t) = -x + \sum_n a_n \sin\left(\frac{2n-1}{2}\pi x\right) \exp\left[-\left(\frac{2n-1}{2}\pi\right)^2 t\right].$$

Inserting into the initial condition $\sigma(x,0) = 0$, we obtain the Fourier coefficients:

$$a_n = \frac{(-1)^{n+1} 8}{(2n-1)^2 \pi^2}$$

The void volume is

$$\Delta V(t) = \frac{1}{2} - \sum_n \frac{(-1)^{n+1} 16}{(2n-1)^3 \pi^3} \exp\left[-\left(\frac{2n-1}{2}\pi\right)^2 t\right].$$