IMMORTAL INTERCONNECTS—
PREVENT CRACKING AND LIMIT VOID SIZE

Z. SUO[1], Q. Ma[2] and W.K. Meyer[2]
[1]Mechanical and Aerospace Engineering Department and Princeton Materials Institute, Princeton University, Princeton, NJ 08544.
[2]Intel Corporation, Components Research, 2200 Mission College Blvd., Santa Clara, CA 95052.

ABSTRACT

This paper considers an aluminum line in a multilevel interconnect structure. Upon cooling from the processing temperature, differential thermal contraction causes a triaxial tensile stress state in the aluminum line; voids may initiate and grow to relax the stress. When a direct voltage is applied, the electric current causes aluminum atoms to diffuse. The interconnect will evolve to a state with a high pressure at the anode, and a large void at the cathode. The pressure may crack the surrounding insulator or debond an interface, extruding aluminum. The void may uncover the via contact area, substantially increasing electrical resistance. Provided neither failure mode occurs, aluminum electromigration will stop and the interconnect will function forever. This paper examines the conditions under which the interconnect is immortal.

INTRODUCTION

Figure 1 shows a TEM cross-section of a multilevel interconnect structure. On a silicon chip (not shown in the figure), interconnects are made of several levels of aluminum lines. Silicon dioxide fills the space in between to provide electrical insulation and structural support. Tungsten vias link the aluminum lines between different levels. Titanium aluminide layers shunt the electric current where voids deplete aluminum. Also shown in Fig. 1 is a schematic of one aluminum line encapsulated in an oxide tube. Under normal operation conditions, electrons enter and leave the tube from the tungsten vias, but aluminum atoms stay inside the tube.

The aluminum line evolves over time. Figure 2 summarizes the main observations. Because aluminum has a thermal expansion coefficient much larger than the other materials on the chip, upon cooling from the processing temperature (Fig. 2a), the aluminum line is under a state of tensile stress [1-4]. Due to the constraint of the oxide, the tensile stress in the aluminum line is triaxial, having a hydrostatic component several times the yield strength of aluminum.

If the structure is left at a low temperature for a period of time (Fig. 2b), voids initiate in the line, and enlarge as aluminum atoms diffuse into the remainder of the line to relieve the tensile stress [5,6]. Far below the processing temperature, thermal misfit is large but diffusivity is low, so that it takes time for the stress to be relieved completely. Provided these voids are small and separated, they increase electrical resistance slightly. Of course, after a sufficiently long time, the stress will be completely relieved. Furthermore, the surface energy will motivate the small voids to coarsen into a single large void.

Once a direct voltage is supplied (Fig. 2c), electrons enter the aluminum line from one tungsten via (cathode), and leave from another (anode). The electron wind causes aluminum atoms to diffuse toward the anode. The voids exhibit extraordinarily complex dynamics: they nucleate, disappear, drift, change shape, coalesce, and break up [7,8]. The detailed behavior is sensitive to the microstructure, namely, the orientations of aluminum grains, and the conditions of various interfaces. The computational tools so far cannot predict the complex dynamics, and may never will.

Despite the commotion in the transient, the end state (Fig. 2d) is simple [9-11]. After a long time, only a single void remains near the cathode. Voids in the middle of the line have now been all filled. As the void at the cathode grows, atoms diffuse into the rest of the line, inducing a distribution of pressure. In this end state, the aluminum line is analogous to a liquid column in the gravity field: the pressure increases linearly with the depth, leaving all the void space on the top. It is this pressure gradient that stops electromigration. The atoms that pressurize the line also give a void volume in addition to that given by the differential thermal contraction. The interconnect stays in this state afterwards, until the temperature or the voltage changes again.

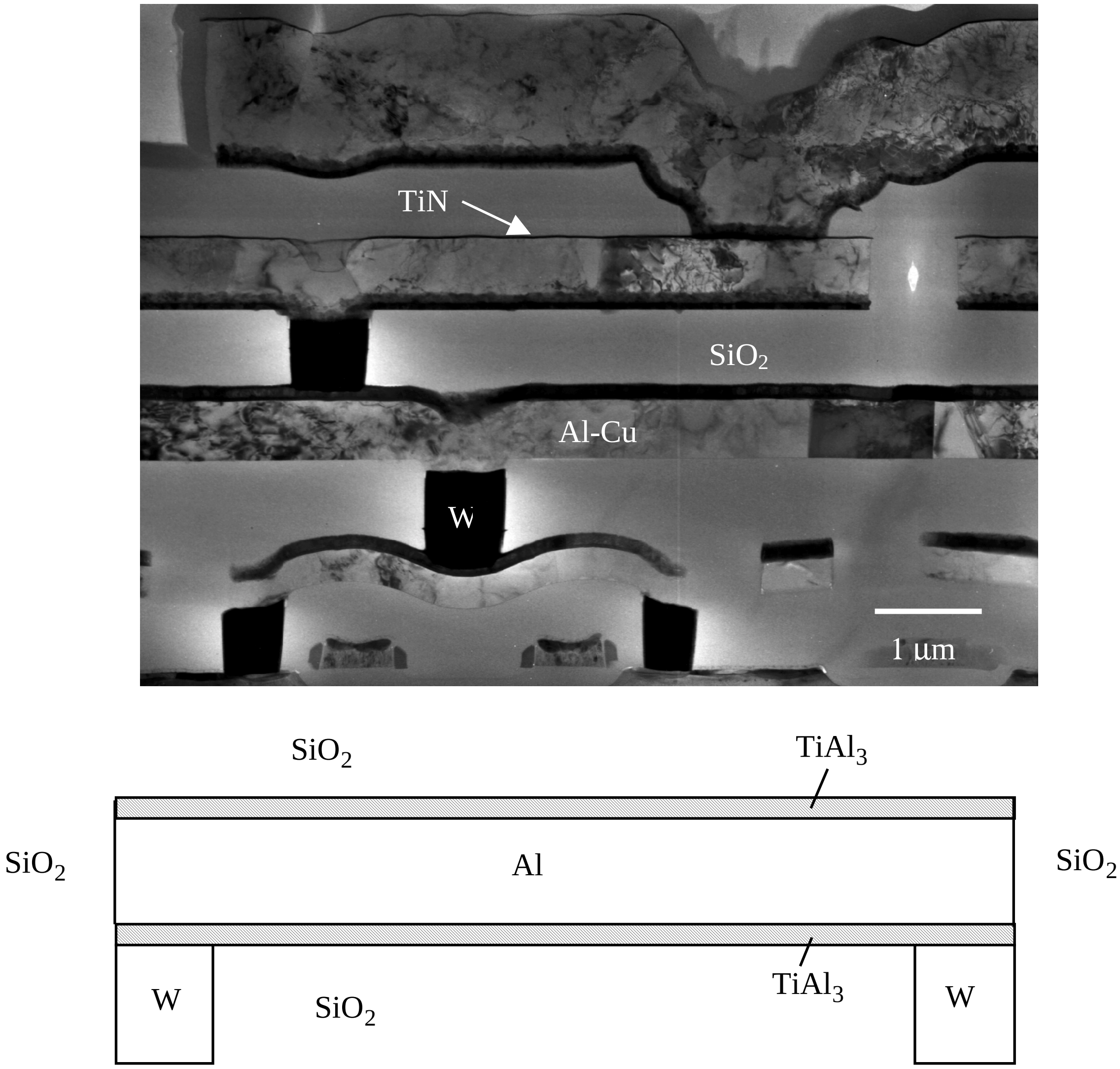

Figure 1 Top: A TEM cross-section of a multilevel interconnect structure (Courtesy of John Mardinly, Intel Corp). Bottom: A schematic of one interconnect line.

Two aspects of the end state call for attention: the pressure and the void. The pressure in the aluminum line near the anode may crack the surrounding oxide, extruding aluminum (Fig. 3). The interfaces between various materials in the structure may also debond. The saturated void size affects the electrical resistance. If the saturation void length is small compared to the diameter of the tungsten via (Fig. 4a), the change in the electrical resistance is small. If the saturation void is long compared to the diameter of a tungsten stud, the electric current has to flow along the shunt layers, and the change in the electrical resistance is large. Provided that fracture is averted and the resistance increase is small, the end state gives a simple perspective on interconnect reliability. One can focus on the end state itself, rather than the rate processes to reach it. It plays down the roles of the time scale, the rate processes, and the microstructure of aluminum. No longer need the microstructure be optimized for slow mass transport or low void nucleation rate. Nor is performance sensitive to temperature. The reliability is warranted by energetics, rather than kinetics, and is therefore much more robust. This perspective is particularly useful for short aluminum lines, where the characteristic time for diffusion is short, and the saturation void volume is small. This paper summarizes the conditions to avert cracking and excessively large voids.

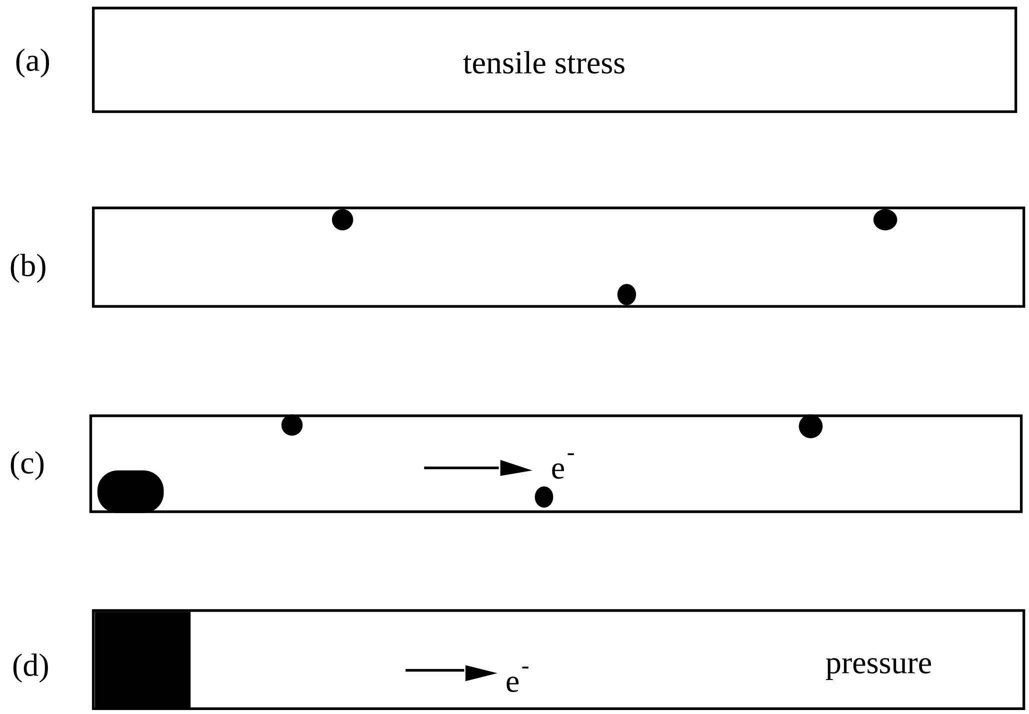

Figure 2 An evolving interconnect subject to a temperature change and a direct voltage. (a) Right after cooling from the processing temperature, differential thermal contraction causes a triaxial tensile stress state in the aluminum line. (b) Voids grow to relax the stress. (c) When a direct voltage is applied, the electric current causes aluminum atoms to diffuse toward the anode. (d) After a sufficiently long time, a steady-state is reached: a single void remains at the cathode, a pressure gradient sets up in the aluminum line, and electromigration stops.

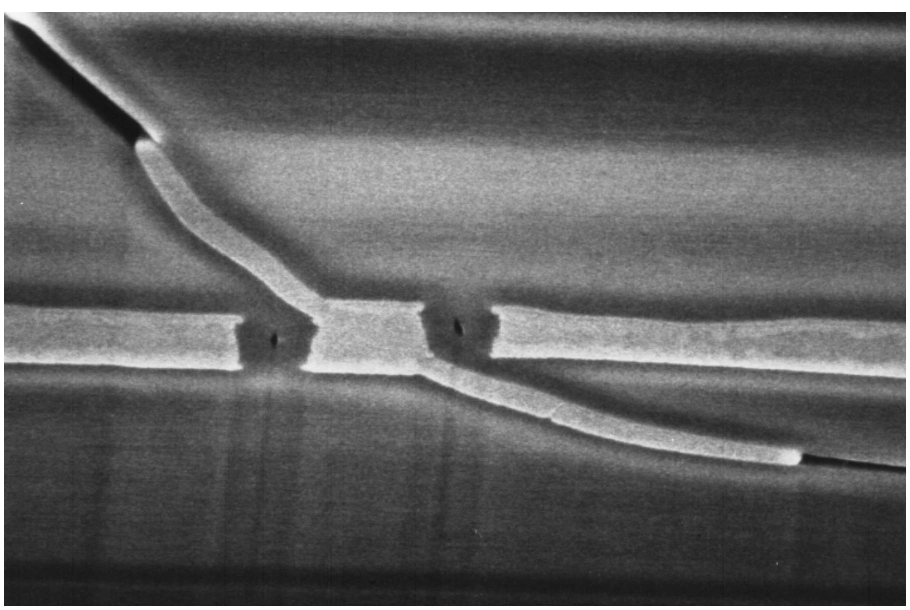

Figure 3 The aluminum line in the middle carries an electrical current in the direction perpendicular to the paper. The pressure in the aluminum line causes the silicon dioxide to crack, and aluminum to extrude.

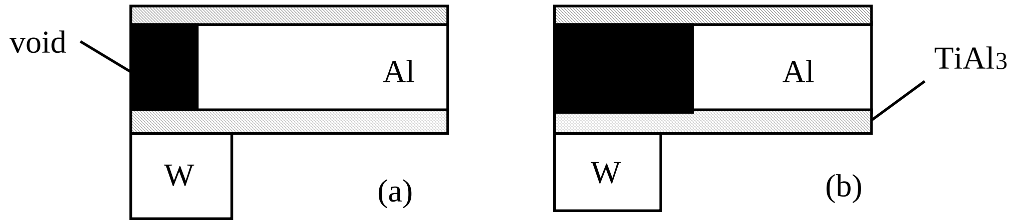

Figure 4 (a) Void length smaller than tungsten via diameter. (b) Void length larger than tungsten via diameter.

CONDITION TO PREVENT CRACKING

When a direct voltage is applied, the moving electrons in the aluminum line impart momentum to aluminum atoms, motivating the atoms to diffuse toward the anode. Because atomic diffusion through the insulator and the vias is negligibly slow, the aluminum line is confined in space, much like a liquid column in a glass tube. As aluminum atoms diffuse, a pressure gradient sets up in the line. Diffusion stops when the pressure gradient balances the electron wind force. Consequently, in the steady-state, the pressure is linearly distributed along the aluminum line. The pressure at the anode needed to stop diffusion is given by the Blech equation [12]:

$$p = Z^* eV / \Omega , \tag{1}$$

where Z^* is the effective valence, e the elementary charge, V the applied voltage, and Ω the volume per atom. In [11], for example, it was stated that for 100 μm lines tested under various current densities, aluminum did not extrude under $0.56 \times 10^{10} \mathrm{A/m^2}$, but did extrude under $1.0 \times 10^{10} \mathrm{A/m^2}$. Using line length L = 100 μm, current density j = $1.0 \times 10^{10} \mathrm{A/m^2}$, as well as physical parameters $Z^* = 5$, $e = 1.6 \times 10^{-19} \mathrm{C}$, $\rho = 3 \times 10^{-8} \Omega \mathrm{m}$, and $\Omega = 1.66 \times 10^{-29} \mathrm{m^3}$, one finds from (1) that the pressure needed to crack the oxide is p = 1.5 GPa. The values of j and Z^* used above are not accurately known. These uncertainties aside, electromigration will induce tensile stresses in the oxide that are much larger than typical strength of the oxide in bulk.

The oxide on the chip can sustain a large tensile stress because flaws are small. The fabrication process controls the geometry all the way to the feature size, so that cracklike flaws must be smaller than the feature size. Use the linewidth, w, as a representative size scale. The oxide around an interconnect cannot crack if the Griffith condition is satisfied [13]:

$$\beta \frac{p^2 w}{E} < \Gamma . \tag{2}$$

Here Γ is the fracture energy of the oxide, E Young's modulus of the oxide, 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 $\beta = 0.25$, $\Gamma = 4 \mathrm{J/m^2}$, $E = 70 \mathrm{GPa}$, and w = 0.5 μm, one finds from (2) that the oxide can sustain anode pressure up to $p = 1.5 \mathrm{GPa}$. That this value is the same as electromigration-induced pressure estimated above is fortuitous. However, both (1) and (2) are insensitive to details: they should give correct orders of magnitude.

Combining (1) and (2), we obtain the condition under which the electron wind cannot cause the insulator to crack:

$$V \sqrt{\beta w} < \frac{\Omega (E \Gamma)^{1/2}}{Z^* e} . \tag{3}$$

The right-hand side collects physical constants, and the left-hand side the design variables. Because β depends on the anode geometry, a systematic calculation would rank possible shapes.

In the above, thermal stresses in the oxide 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 end 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.

At the deposition temperature, the dielectrics may develop large intrinsic stresses, which are unrelated to the volume change of aluminum, and persist under temperature change and current. Another circumstance involves an aluminum line tested under a voltage up to the end state, and then brought to a higher temperature. Instantaneously the thermal expansion misfit between aluminum and oxide adds more tensile stress in the insulator. In such cases, the additional stresses must be included to modify the cracking condition.

SATURATED VOID VOLUME

The vias and the insulator prevent mass from entering or leaving the aluminum line, so that the total number of aluminum atoms in the line is conserved. First consider the temperature drop alone. Imagine separately a free standing aluminum line, and a tubular cavity in the oxide that should have been occupied by the line. When the temperature drops from the processing temperature by ΔT, both the line and the cavity contract. The volume strain of the aluminum line is $3\alpha_{\mathrm{Al}}\Delta T$, where α_{Al} is the thermal expansion coefficient of aluminum. The relative volume change of the cavity is $3\alpha_{\mathrm{eff}}\Delta T$, where α_{eff} is an effective thermal expansion coefficient of a value between those of the oxide and the silicon substrate. The misfit volume strain between the line and the cavity is $3(\alpha_{\mathrm{Al}} - \alpha_{\mathrm{eff}})\Delta T$. Because aluminum has a much larger thermal expansion coefficient than either the oxide or the silicon substrate, the exact value of α_{eff} is unimportant in estimating the misfit. Now allow the aluminum line to reside in the cavity. When the stress in the line is completely relaxed, the thermal expansion misfit is fully accommodated by the void space. Next consider a line subject to a direct voltage. The electric current causes aluminum atoms to insert at the grain boundaries or the interfaces, and be accommodated by elastic deformation. This gives an additional void volume. The ratio of the void volume to the aluminum line volume is given by $Z^{*}eV/2\Omega B$, where B is an effective elastic modulus [14].

Let v be the volume of the free-standing aluminum line, and v_1 be the volume of the void. The relative void size due to the combined effects of the temperature change and the voltage is [13]

$$\frac{v_1}{v} = 3(\alpha_{\mathrm{Al}} - \alpha_{\mathrm{eff}})\Delta T + \frac{Z^{*}e}{2\Omega B}V. \tag{4}$$

As stated above, the critical state is that all the small voids collect into a single void at the cathode. When the void is larger than the tungsten via diameter, the void may substantially increase the electrical resistance. Taking $\alpha_{\mathrm{Al}} - \alpha_{\mathrm{eff}} = 20\times10^{-6}\mathrm{K}^{-1}$ and ΔT = 200 K (corresponding to the drop from the processing temperature to a temperature typical for an electromigration test), one finds from (4) that the temperature change contributes to 1.2% relative void size. Taking $p_A = 1.5$ GPa and B = 50 GPa, one finds from the applied voltage contributes 1.5% relative void size. For a 10 μm long aluminum line, the saturated void length will be about 0.3 μm. For a 100 μm long aluminum line, the saturated void length will be about 3 μm. Consequently, the end state is likely to be tolerated by a short aluminum line, but not by a long aluminum line. Also note that the saturated void volume due to thermal misfit alone is quite large. Normally there may be several small thermal voids along a line, and by themselves may be harmless. A small voltage, however, can sweep these voids to the cathode and turn them into a single large void.

TIME SCALE

To plan experiments, one would like to know the time scale over which an interconnect reaches the end state. A dimensional consideration dictates that the time scale for any event involving mass transport over the entire line length, L, be [14]

$$\tau = \eta \frac{L^2 kT}{DB\Omega}, \tag{5}$$

where η is a dimensionless number depending on the chosen event, e.g., attaining a half of the saturation void length. Note that the time scale is independent of the applied voltage. A large voltage transports mass at a high rate, but also needs to transport more mass to reach the stable state. The diffusivity is sensitive to temperature and microstructure, and so is the time scale. To accelerate experiments, one may use short lines at high temperatures. The estimate (5) assumes that void nucleation at the cathode end is fast compared to mass transport over the line length.

CONCLUDING REMARKS

When a temperature and a voltage is newly established, an interconnect adapts to the change by evolving into a stable state, with a single void at the cathode end, and a linear pressure distribution in the rest of the line. This stable state arises from three features of interconnect structures: the aluminide layers shunt the electric current where the void depletes aluminum, the tungsten vias and the oxide prevent aluminum atoms from leaving or entering the line, and the oxide provides the stiffness to contain the pressure. Although thermal voids are typically small, the sum of their volumes is significant. Even under a small electric current density, these small voids are gradually filled at the expense of aluminum at the cathode end, leading to a large resistance increase. Provided that fracture is averted and the resistance increase is small, the stable state gives a simple perspective on interconnect reliability. It plays down the roles of the time scale, the rate processes, and the microstructure of aluminum. No longer need the microstructure be optimized for slow mass transport or low void nucleation rate. Nor is performance sensitive to temperature. The reliability is warranted by energetics, rather than kinetics, and is therefore much more robust. Accelerated tests can also be readily interpreted.

ACKNOWLEDGEMENTS

ZS is grateful to the support of the Institute of Materials Research and Engineering, Singapore, of the National Science Foundation, and of the Intel Corp. Discussions with Dr. R. Rosenberg at IBM are valuable.

REFERENCES

1. R.E. Jones, and M.L. Basehore, *Appl. Phys. Lett.* **50**, 725 (1987).
2. B. Greenebaum, A.I. Sauter, P.A. Flinn, and W.D. Nix, *Appl. Phys. Lett.* **58**, 1845 (1991).
3. Y.-L Shen, S. Suresh, I.A. Blech, *J. Appl. Phys.* **80**, 1388 (1996).
4. Q. Ma, S. Chiras, D.R. Clarke, and Z. Suo, *J. Appl. Phys.* **78**, 1614 (1995).
5. J.T. Yue, W.P. Funsten, and R.V. Taylor, Proc. Int. Reliability Phys. p. 126 (1985).
6. S.A. Lytle and A.S. Oates, J. Appl. Phys. **71**, 174 (1992).
7. E. Arzt, O. Kraft, W.D. Nix and J.E. Sanchez, Jr. J. Appl. Phys. **76**, 1563 (1994).
8. T. Marieb, P. Flinn, J.C. Bravman, D. Gardner, and M. Madden, J. Appl. Phys. **78**, 1026 (1995).
9. C.-K. Hu, M.B. Small, and P.S. Ho, J. Appl. Phys. **74**, 969 (1993).
10. R.G. Filippi, G.A. Biery, and R.A. Wachnik, J. Appl. Phys. **78**, 3756 (1995).
11. R.G. Filippi, R.A. Wachnik, H. Aochi, J.R. Lloyd, M.A. Korhonen, Appl. Phys. Lett., **69**, 2350 (1996).
12. I.A. Blech, J. Appl. Phys. **47**, 1203 (1976).
13. Z. Suo, Acta Materialia. **46**, 3725 (1998).
14. M.A. Korhonen, P. Borgesen, K.N. Tu, C.-Y. Li, J. Appl. Phys. **73**, 3790 (1993).