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Electromigration lifetime and critical void volume

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We study electromigration in copper lines encapsulated in an organosilicate glass. A line fails when a void near the upstream via grows to a critical volume. We calculate the void volume as a function of time. The statistical distribution of the critical volume (DCV) is taken to be independent of testing variables, such as line length and electric current density. By contrast, the distribution of the lifetime (DLT) strongly depends on these testing variables. We deduce the DCV from the experimentally measured DLT. Once deduced, the DCV can predict the DLT under untested conditions. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1821631]

Electromigration behavior on on-chip interconnect structures has been significantly affected by recent changes such as replacing aluminum with copper,[1,2] replacing silica with low-permittivity dielectrics,[3–5] removing shunts,[6,7] and adding caps.[8] This letter studies a fatal failure mode in dual damascene copper lines. As electron flow drives copper atoms to drift in a line, a void forms at the upstream via, grows to a critical volume, and blocks the electron flow (Fig. 1).

In an old generation of interconnect structures, the TiAl layers provided shunts, so that interconnects could be designed to be immortal on the basis of a steady state.[9–12] As atoms drift downstream, a stress field builds up in the line to balance the electron flow: the net atomic flux stops in the steady state. In the new generation of interconnect structures, however, the TaN liners are ineffective as shunts, so that most copper lines are mortal under practical testing conditions.[6,7]

We develop a method to analyze electromigration on the basis of *transient states*. The critical void volume differs from line to line. For example, the critical volume is small if the void forms right beneath the via, and is large if the void forms in the line somewhat off the via.[1,2,6,7] We assume that the distribution of the critical volume (DCV) is independent of testing variables, such as the line length and electric current density. By contrast, the distribution of the lifetime (DLT) varies with these testing variables in complicated ways. Direct observation of the voids for a large number of lines is impractical. We calculate the void volume as a function of time using a transient model.[13] This volume-time function allows us to obtain the DCV from the experimentally measured DLT. Once obtained, the DCV can be used to predict the DLT under untested conditions.

Figure 2 shows the time-to-fail of eight groups of copper lines, obtained from a single wafer at a constant temperature. Each group consisted of 12-18 lines, picked uniformly across the wafer to capture process variation within the wafer. The line length L and the electric current density j are constant for each group of lines, but vary from group to group. Failure of a line was identified by an abrupt increase in the electric resistance. When either L or j was small, the time-to-fail had a large median and a wide dispersion. The time is reported in units of t_*, the median time-to-fail of the group with $L = 70\ \mu\text{m}$ and $j = 23.6\ \text{mA}/\mu\text{m}^2$.

Let the x axis point in the direction of the electron flux, and a void grow at the upstream via, $x=0$. At time t, the stress in the line, $\sigma(x,t)$, is taken to be hydrostatic. Both the electric current and the stress gradient drive the atomic flux: $J=(D/\Omega kT)(Z^* e\rho j+\Omega\,\partial\sigma/\partial x)$, where J is the atomic flux, D the diffusion coefficient of atoms, Ω the volume per atom, k the Boltzmann's constant, T the temperature, Z^* the effective valence, e the elementary charge, and ρ the resistivity.[9] Let θ be the volume fraction of atoms depleted from a segment of the line. This strainlike quantity relates to the stress as $\sigma = B\theta$, where B is an effective elastic modulus. Mass conservation requires that $\partial\theta/\partial t=\Omega\,\partial J/\partial x$. A combination of the above relations gives $\partial\sigma/\partial t=(DB\Omega/kT)\partial^2\sigma/\partial x^2$.[13]

We assume that the line spends its lifetime mostly on growing the void, and neglect the time to nucleate the void. Before the electric current is applied, the stress in the line is

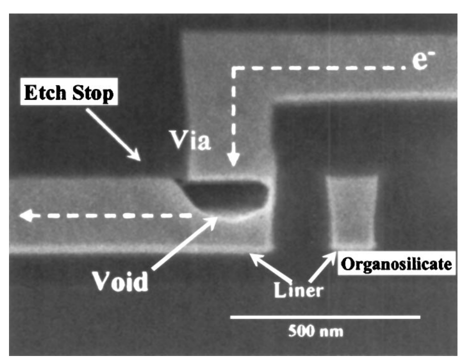

FIG. 1. A void forms underneath a via in the upstream of the lower-level copper line. The liner underneath the via blocks the atomic flux from the upper-level copper line.

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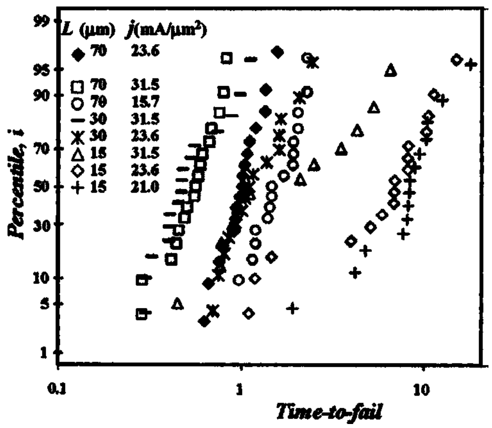

FIG. 2. The distribution of the lifetime (DLT) measured from eight groups of copper lines. The time is scaled by the median time-to-fail of the group with $L=70$ μm and $j=23.6$ mA/μm^2.

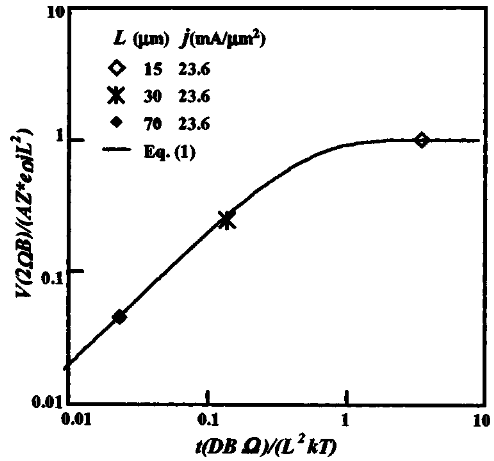

FIG. 3. The void volume as a function of time, Eq. (1). The three data points are the measured values of t_{50} for three groups of lines. By fitting the data points to the curve, we obtain a value for the parameter group $(t^*kT)/(DB\Omega)$.

negligible. After, the stress at the void is taken to be zero, and the atomic flux vanishes at the downstream via. We solve $\sigma(x,t)$ from the above partial differential equation, and calculate the void volume V from the volume of atoms drifted into the line, $V=-A\int_0^L(\sigma/B)dx$, where A is the cross-sectional area of the line. The void volume is a function of time (Fig. 3)

$$\frac{V}{V_{\mathrm{satu}}}=1+\frac{32}{\pi^3}\sum_{n=1}^{\infty}\frac{(-1)^n}{(2n-1)^3}\exp\left[-\left(\frac{2n-1}{2}\pi\right)^2\frac{t}{\tau}\right], \quad (1)$$

where $\tau=(L^2kT)/(DB\Omega)$ and $V_{\mathrm{satu}}=(AZ^*e\rho jL^2)/(2\Omega B)$. In the short-time, long-line limit, $t/\tau\to 0$, the stress in the line is negligible, and the void volume is linear in time, $V=AZ^*e\rho jDt/kT$. In the long-time, short-line limit, $t/\tau\to\infty$, a steady state is attained: the electron current balances the stress gradient, the atomic flux vanishes, and the void attains the saturation volume, V_{satu}. Void growth involves atomic transport over the line length, which averages over many structural entities (e.g., grains). Consequently, we expect that Eq. (1) adequately predicts the void volume as a function of time.

Let t_i be the time below which i percent of lines in a group fail, and V_i be the volume below which i percent of the critical voids lie. For given L and j, Eq. (1) provides a deterministic functional relationship between the two random variables t_i and V_i: $t_i=f(V_i;L,j)$.

We proceed to find a value of the parameter group $(t_*kT)/(DB\Omega)$. Each set of experimental data $(t_{50};j,L)$ can be plotted as a point on Fig. 3. For example, we plot three sets of data $(1;23.6,70)$, $(1.09;23.6,30)$, and $(6.87;23.6,15)$. On this log-log plot, a change in the parameters $(t_*kT)/(DB\Omega)$ and $(2V_{50}\Omega B)/(AZ^*e\rho)$ translates all the data points by the same amount. To fit the three points to the theoretical curve, we find that $(t_*kT)/(DB\Omega)=1.12\times 10^{-10}$ m^2.

We obtain the DCV using the DLT measured from a single group of lines. Inserting the experimental values of t_i for the group for which $L=70$ μm and $j=23.6$ mA/μm^2 into Eq. (1), and using the value of $t_*kT/DB\Omega$ obtained above, we obtain the corresponding values of $(2V_i\Omega B)/(AZ^*e\rho)$, which are listed in Table I.

Once the DCV is known, Eq. (1) predicts the DLT for any j and L. Figure 4 plots the experimental values of t_i for the eight groups of the lines against the values of V_i in Table I. The agreement between the theoretical curve and the experimental data is encouraging.

Figure 3 indicates that the same variation in the critical volume causes a narrow lifetime dispersion for large j and L, but causes a wide lifetime dispersion for small j and L. This explains the trend of the experimental data in Fig. 2 and those reported by others.[7] From Eq. (1), a dimensionless measure of the lifetime dispersion, such as the sigma (the standard deviation of ln t_i), is expected to be a function of jL^2. Figure 5 compares the predicted dispersion to the experimental data for the eight sets of data. The agreement is again encouraging.

Recall that $V_{\mathrm{satu}}=(AZ^*e\rho jL^2)/(2\Omega B)$. If $V_{\mathrm{satu}}=V_i$, the saturation void volume exceeds the critical volume of i percent of the lines. Consequently, $(jL^2)_i=(2V_i\Omega B)/(AZ^*e\rho)$ is the value of the jL^2 product below which i percent of the lines are mortal. Unfortunately, all the lines tested for this work are mortal, and our data do not fit very well with the theoretical curve at the long-time limit (Fig. 4). Nonetheless, the three groups of the lines, tested at small values of jL^2 (4.73, 5.18, 7.01 A), show large lifetime dispersion, indicative of approaching the immortality conditions. These jL^2 values are of the same order of magnitude as those listed in Table I.

The above procedure estimates the median critical volume V_{50} as $V_{50}/A=145$ nm. (We take $\rho=4.0\times 10^{-8}$ Ωm, Ω

TABLE I. The distribution of the critical void volume (DCV). The parameter group has the same unit as the electric current, A.

Percentile i	10	20	30	40	50	60	70	80	90
$(jL^2)_i=2V_i\Omega B/AZ^*e\rho$	7.16	8.44	9.72	10.1	10.6	10.9	11.5	13.0	14.6

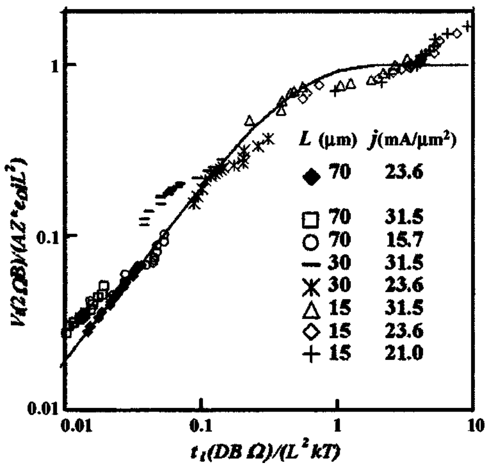

FIG. 4. The curve is a plot of Eq. (1), which provides a deterministic relation between the two random variables, V_i and t_i: $t_i = f(V_i; L, j)$. Knowing V_i (Table I), the curve predicts t_i for given testing variables L and j. The theoretical curve is compared with the experimental values of t_i for the eight groups of the lines.

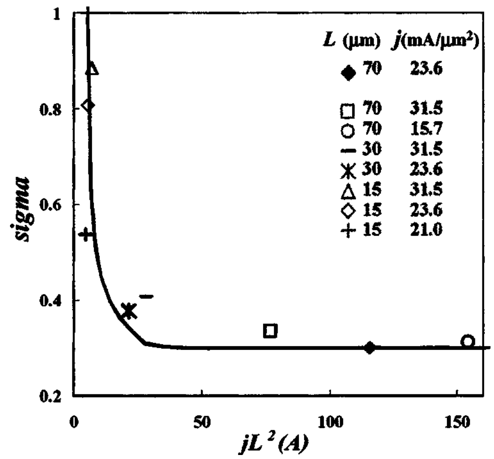

FIG. 5. The standard deviation of ln t_i, sigma, as a function of jL^2. The data points are obtained from the eight groups of lines reported in Fig. 2. The curve is plotted using Eq. (1), which predicts t_i from $t_i = f(V_i; L, j)$, using the values of V_i in Table I.

$= 1.18 \times 10^{-29}$ m^3, $Z^* = 1.0$, and $B = 10$ GPa.) An inspection of the micrograph in Fig. 1 gives another estimate: 115 nm. We can estimate the critical volume from yet another consideration. For small voids, their shape is largely determined by the surface energy, and the electric current density is a weak driving force at this size scale.[14] Neglect the anisotropy in the surface energy, and assume that the surface diffusion is fast compared to the transport along the line. The critical void takes the equilibrium shape of a spherical cap underneath the via, its base diameter coinciding with the via size d, giving the volume

$$V_{\text{crit}} = \frac{\pi d^3}{12}\left(\frac{1}{1 - \cos \Psi} + \frac{\cos \Psi}{2}\right)\sin\Psi, \tag{2}$$

where Ψ is the wetting angle of copper on the liner. The critical volume increases as the wetting angle decreases. Taking $\Psi = 90°$, $d = 250$ nm, and $A \approx d^2$, we find that $V_{\text{crit}}/A = 98$ nm. The three independent estimates give similar results, which provide support for our approach.

In summary, this letter relates the electromigration lifetime to the critical void volume. The line length and current density affect the statistical distribution of the lifetime, but they do not affect that of the critical void volume. The DCV can be deduced from the DLT under one set of the testing conditions, and then used to predict the DLT under untested conditions.

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