Projecting Interconnect Electromigration Lifetime for Arbitrary Current Waveforms

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Abstract—We propose a vacancy relaxation model which predicts that dc lifetime is \( A_0(T) / J^n \), pulse dc (arbitrary unidirectional waveform) lifetime is \( A_0(T) / J^{n-1} \), pure ac lifetime is \( A_0(T) / \sqrt{J} \), and ac-plus-de-bias lifetime is \( A_0(T) / J^{n-1} \) for all waveforms and all frequencies above 1 kHz. These predictions are verified by experiments and significantly raise the projected lifetimes beyond the widely assumed \( A_0(T) / J^{n/2} \). The pure ac lifetimes of aluminum interconnect are experimentally found to be more than 10 times longer than dc lifetime for the same current density. In addition, ac stress lifetimes are observed to follow the same dependences on current magnitude and temperature, for \( T < 300^\circ \text{C} \), as the dc stress lifetime.

I. INTRODUCTION

THE electromigration failure of Al interconnect has been extensively studied under constant current conditions. Integrated circuits, however, often operate with time-varying unidirectional (pulse dc) or bidirectional (ac) current waveforms. For the case of unidirectional currents (which are found in the power bus lines), the assumption is often made that the conductor lifetime increases linearly with the reciprocal of the duty factor (i.e., the total on-time to failure is the same in constant dc and pulse dc experiments). However, our experimental results, as well as those of others [1]–[4] indicate considerably larger pulse dc lifetime than predicted by this simple model. As for the case of ac conditions (which is found in signal lines of MOS and CMOS circuits), the proper method of predicting lifetime becomes even less obvious because the direction of current is time-varying and so is the flux of Al atoms in the interconnect. The question is often asked whether electromigration lifetime under pure ac connect is very long because of the reversible flow of atomic flux, or is not very different from the dc stress lifetime. Finally, there is the case of ac current with a nonzero dc component. We present a theoretical model that predicts the correlations among the lifetimes under these conditions and the constant current stress lifetime, which can be measured easily. The objective of our work is to apply this model to predict pulse dc and ac lifetimes under arbitrary current waveforms and frequencies using constant dc stress results.

II. MODEL

Fig. 1 illustrates the general model [5]. Let \( \delta \) be the volume of the void (or some other measure of the damage which eventually leads to failure) in the interconnect. The rate of increase of \( \delta \) should be proportional to the vacancy flux \( F_\delta \) which is equal to the product of vacancy concentration \( n \) and vacancy velocity \( v \). The velocity has been shown to be proportional to the current density \( J \), independent of pulse duty factor (0.02–0.9) and frequency \((0.01\text{–}10^8 \text{ Hz})\) in the pulse dc experiment [1]. The time derivative of \( \delta \) can be written as

\[
\frac{d\delta}{dt} \propto n \nu \propto nJ
\]

(1)

\[
= R(\delta) n(t) J(t).
\]

(2)

The proportionality constant \( R \) is allowed to be a function of \( \delta \), i.e., varying during the stress, for generality. The time-to-failure (TTF) is the time required for \( \delta \) to reach some critical value \( \delta_c \)

\[
\int_0^{TTF} n(t) J(t) \, dt = \int_0^{\delta_c} R(\delta) \, d\delta = K.
\]

(3)

One may define TTF as the median time-to-failure (MTF), or 1% population failure time, or any other failure time. Assuming that the vacancy relaxation time is \( \tau \) and the vacancy generation rate is proportional to \( J^{m-1} \) (the use of exponent \( m - 1 \) will be justified later) with a proportionality constant \( \alpha \). Please note that the characteristic time \( \tau \) affects both the vacancy buildup and decay process. It is analogous to the recombination time of holes and electrons in semiconductor or the time constant in charging RC network.

\[
\frac{dn}{dt} = -\frac{n}{\tau} + \alpha |J(t)|^{m-1}.
\]

(4)

The absolute sign is used here because the number of vacancies generated depends on the number of electrons available for momentum transfer to the lattice and does not depend on the direction of electron flow. For a given waveform \( J(t) \), one can solve (4) for \( n(t) \) and substitute \( n(t) \) into (3) to find the TTF.

**DC Case:** Using (3) and (4)

\[
n = \frac{\tau \alpha J_\infty^{m-1}}{\tau \alpha J_{\infty dc}^{m-1}},
\]

(5)

\[
\text{TTF}_{dc} = \frac{K}{\tau \alpha J_{\infty dc}^{m-1}}.
\]

(6)

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Fig. 1. In dc and pulse dc cases, the volume of the void \( \delta \) increases with time at a rate proportional to the product of vacancy concentration \( n \) and velocity \( v \). In pure ac case, the volume of void grows during the first half cycle in (a) and decreases in (b) during the opposite current period. As a result, the proportionality constants \( R_+ \) and \( R_- \) in (12) are different.

By observation, \( K/\tau \alpha \) is simply equal to the \( A_{dc}(T) \) in the Black’s equation [6]

\[
TTF_{dc} = \frac{A_{dc}(T)}{J_0^{n-1}}.
\]

(7)

The reason for choosing the functional form of vacancy generation rate as \( J^{n-1} \) is now obvious.

**Pulse DC Case:** The vacancy relaxation time \( \tau \) is about 1 ms [7]. For all frequencies much higher than \( 1/\tau \), i.e., above 1 kHz, \( n(t) \) reaches steady-state value after a few \( \tau \)'s and consists of a small ripple superimposed on an average \( \bar{n} \). \( \bar{n} \) can be obtained by taking the time average of every term in (4), and realizing that left-hand side of (4) integrated over one period is zero

\[
n(t) \approx \bar{n} = \tau \alpha J^{n-1}.
\]

(8)

The total time to failure which indicates the on-time and off-time of the waveform is

\[
TTF_{pulsedc} = \frac{K}{\tau \alpha J^{n-1}} = \frac{A_{dc}(T)}{J^{n-1}}.
\]

(9)

where \( A_{dc}(T) \) is the same as that obtained from dc measurement (7). For the special case of rectangular dc pulses, \( TTF_{pulsedc} \) can be related to \( TTF_{dc} \) with \( J_{dc} = J_{peak} \) for all exponent values \( m \) except for \( m = 1 \) by

\[
TTF_{pulsedc} = TTF_{dc} \left( \frac{duty\,factor}{2} \right)^2.
\]

(10)

For the case of \( m = 1 \) and \( m = 2 \), (9) becomes

\[
TTF = \frac{A_{dc}(T)}{J^n}.
\]

(11)

**A. Pure AC Case**

The time derivative of \( \delta \) can be written as

\[
\frac{d\delta}{dt} = R_-(\delta)n(t)J(t)
\]

during the positive cycle and

\[
\frac{d\delta}{dt} = -R_+(\delta)n(t)J(t)
\]

during the negative cycle. At any given \( \delta \), the values and the signs of \( R_+(\delta) \) and \( R_-(\delta) \) are in general not the same. The nonsymmetrical flow of vacancy flux due to the geometry of the interconnect (e.g., near the bond pads) or at grain boundary triple point can give rise to different values of \( R_+ \) and \( R_- \). The latter effect can be inferred from Fig. 1. The negative sign in front of \( R_- \) represents the probable existence of healing effect by current of opposite polarities. However, \( R_- \) can take on a negative sign if the void is enlarged by current of both polarities. Therefore, (12) are quite general.

The vacancy generation rate is independent of the sign of current density. Taking the time average of (4) yields

\[
n(t) = \bar{n}_{ac} = \tau \alpha \frac{J}{|J|} |J|^{n-1}.
\]

(13)

Summing the damage in one period \( \Delta t \) using (12)

\[
\frac{d\delta}{dt} = \frac{R_+(\delta) - R_-(\delta)}{2} \tau \alpha \frac{J}{|J|} |J|^{n-1}.
\]

(14)

The factor of half comes from the fact that for pure ac waveform, the time integral of the current density over the positive cycle is equal to the integral over the negative cycle, and is equal to one half the time average of \( |J| \) in one period. Following the procedure of (3)

\[
TTF_{ac} = \frac{2}{\tau \alpha \bar{n}} \frac{\int_0^\delta R_+(\delta) - R_-(\delta) d\delta}{|J| |J|^{n-1}}
\]

\[
= \frac{A_{ac}(T)}{|J| |J|^{n-1}}.
\]

(15)

Please note the \( A_{ac}(T) \) has no direct correlation with \( A_{dc}(T) \). Therefore, at least one ac test using a convenience waveform and frequency, e.g., 10-kHz square wave, needs to be carried out in order to determine \( A_{ac}(T) \). Subsequently, (15) can be used to predict \( TTF_{ac} \) for other current waveforms, magnitudes and frequencies.

**B. General AC Case**

Equations (12) can be extended to derive the TTF for bidirectional current waveform with dc bias. Consider a bidirectional waveform consisting of two components of opposite polarities: the component with the larger time average is designated as the major component \( J_m(t) \) and the other the compensating component \( J_c(t) \). Define the time average of the two components with \( \Delta t \) being the period of one cycle

\[
\bar{J}_m = \frac{1}{\Delta t} \int_0^\Delta t |J_m(t)| \, dt
\]

(16a)

\[
\bar{J}_c = \frac{1}{\Delta t} \int_0^\Delta t |J_c(t)| \, dt.
\]

(16b)
Note that $\bar{J}$ and $\tilde{J}$ are positive. According to our definition, $\bar{J} = 0$ for pulse dc waveform and $\tilde{J} = \bar{J}$ corresponds to pure ac waveform.

The time average of the current is

$$\bar{J} = \frac{1}{\Delta t} \int_{0}^{\Delta t} |J(t)| - |J_c(t)| \, dt$$

and the average of the absolute current density is

$$|\bar{J}| = \bar{J}_m + \bar{J}_c.$$  \hspace{1cm} (18)

The steady-state vacancy concentration $\bar{n}$ from (13) is

$$\bar{n} = \tau \alpha |\bar{J}|^{m-1}.$$  \hspace{1cm} (19)

The damage in one period is

$$\frac{\Delta \delta}{\Delta t} = R_+ (\bar{n}) \bar{J}_m - R_- (\bar{n}) \bar{J}_c$$

$$= R_+ (\bar{n}) \bar{J}_m - R_- (\bar{n}) \bar{J}_c + (R_+ (\bar{n}) - R_- (\bar{n})) \bar{J}_c.$$  \hspace{1cm} (20)

Substituting (19) for $\bar{n}$ and using (17) and (18) for $\bar{J}_m$ and $\bar{J}_c$,

$$\frac{\Delta \delta}{\Delta t} = \tau \alpha |\bar{J}|^{m-1} R_+ \bar{J}$$

$$\cdot \left[ 1 + \frac{(R_+ - R_-) (|\bar{J}| - \bar{J})}{2R_+} \right].$$  \hspace{1cm} (21)

In the special case of pure ac, $\bar{J}$ in the first term on the right-hand side of (20) becomes zero and (20) reduces to (15). Typically, the second term is negligible because, as will be shown later, $R_+ R_- \approx R$ and $R_+ - R_- \approx R$ is many orders of magnitude smaller than $R$. With these approximations and following the procedure of (3)

$$\text{TTF}_{ac/dc} = \frac{A_{\delta c}(T)}{|\bar{J}|^{m-1} \bar{J}} \left[ 1 + \frac{A_{\delta c}(T) (|\bar{J}| - \bar{J})}{A_{\delta c}(T) (|\bar{J}| - \bar{J})} \right].$$  \hspace{1cm} (22)

For the special case of $m = 2$, (21) becomes

$$\text{TTF}_{ac/dc} = \frac{A_{\delta c}(T)}{|\bar{J}| \bar{J}} \left[ 1 + \frac{A_{\delta c}(T) (|\bar{J}| - \bar{J})}{A_{\delta c}(T) (|\bar{J}| - \bar{J})} \right].$$  \hspace{1cm} (22)

III. EXPERIMENT DESIGN

Al-2%Si film of 800-Å thickness was sputter-deposited in a CPA 9900 sputtering system onto patterned silicon wafers covered with 400-Å SiO$_2$. The small thicknesses were chosen to minimize heat dissipation and thermal resistance of the test lines so that high current densities may be used in the tests. A liftoff process was used to fabricate groups of 1.2- and 2.2-μm-wide, 100-, 800-, and 1600-μm-long test stripes. Prior to electrical testing, the wafers were annealed at 400°C for 20 min in forming gas. The sheet resistance of the Al-2%Si film was 360 mΩ/square. The test structures were unpassivated. Testing was performed by placing the wafers on the heated stage of a probe station. Current was passed through the test stripes by using a probe card.

Pulse dc and ac currents were generated from a transistor current source driven by the output a TTL gate (Fig. 2). AC current with dc bias was obtained by adding the bias circuit in the lower right of Fig. 2. The setup had six current sources to stress six stripes simultaneously. The output impedance of the current source was large enough to ensure that the variation in the stripe resistance would have no effect on the stress current. Prior to testing, the temperature coefficient of Al line resistance was obtained in order to determine the temperature rise due to self-heating of the test stripes under current stressing. During stressing, a Keithley 196 digital multimeter was used to mea-
ure resistance of the test stripes without interrupting the
current stressing in spite of the time-varying stress current
in the test stripe. This was possible by using the compen-
sated mode of the multimeter and the fact that the instru-
ment has low bandwidth. Open failure was used as the
failure criterion in our testing. TTF data were collected
from six stripes for each test condition. Median TTF was
found by assuming a log-normal failure distribution, and
was adjusted for stripe temperature once the activation
energy was determined.

Rectangular pulse dc and ac current waveforms of peak
current densities from $1 \times 10^7$ to $6 \times 10^7$ A/cm$^2$ in the
frequencies range of 30 kHz to 25 MHz were used in this
work. The current waveform imposed through any of the
test stripes could be monitored with an oscilloscope. An
example of the ac waveform is shown in Fig. 3.

The test stripes were designed following the recom-
mandation of Schafit [8] to reduce the temperature gra-
dient at both ends of the line. We measured the thermal
resistance of the 1-μm-wide test stripe and found that the
temperature rise under dc current density of $2 \times 10^7$A/cm$^2$ was 22°C. The thermal time constant was esti-
ated to be 0.02 μs [9].

IV. RESULTS AND DISCUSSION

A. Pulse DC

The effect of duty factor on MTF for stripes stressed by
rectangular current pulses at frequency of 2.5 MHz is
shown in Fig. 4. Although the peak current density of the
pulse was $1 \times 10^7$ A/cm$^2$, there is minimal self-heating
in these tests, i.e., less than 10°C for dc current (100%
duty factor). Included in Fig. 4 are pulse dc results from
various previous studies [2]-[4]. Their data and ours fit
the following relationship with duty factor:

$$MTF_{pulse\, dc} = MTF_{dc}(duty \, factor)^{-2} \quad (23)$$

This is in agreement with (10) for the special case of rect-
angular dc.

Equation (9) suggests that if $m = 2$, $MTF_{pulse\, dc}$ can
simply be calculated by substituting the time-averaged
current density $\bar{J}$ in Black’s equation (7). The result will
be applicable to arbitrary unidirectional waveforms. This
is verified experimentally for rectangular, triangular, and
bell-shaped waveforms in Fig. 5. These waveforms were
generated by adding a capacitor from the base of the tran-
sistor to ground in Fig. 2.

B. Pure AC

Our preliminary ac result shows that ac lifetime is $10^4$
times larger than dc lifetime for the 800-μm-long stripes
stressed with a peak current density of $1 \times 10^7$ A/cm$^2$ 
(Fig. 6). The failure sites of all six stripes were located
near the middle of the stripe (Fig. 7).

AC MTF obtained from full duty, symmetrical rectan-
gular waveforms (i.e., equal widths and heights in posi-
tive and negative halves of the waveform) of various fre-
quencies (100 kHz-2 MHz) is plotted against current
Fig. 7. Photograph of failure site in 800-μm-long, 1.2-μm-wide, and 0.08-μm-thick stripe stressed with pure ac current and a scanning-electron micrograph of the failure site. Stress condition: $J = 1.0 \times 10^7 \text{ A/cm}^2$; 25 MHz; $T = 250^\circ\text{C}$.

densities in Fig. 8. In order to obtain ac lifetime results in reasonable length of time, we used peak current densities from $2 \times 10^7$ to $6 \times 10^7 \text{ A/cm}^2$ with 100-μm-long, 1.2-μm-wide, and 800-Å-thick stripes in all ac testing. For comparison, the dc MTF for the same stripes is included in Fig. 8. The data plotted in Fig. 8 were corrected for the actual stripe temperature and normalized to 250°C using measured ac and dc MTF activation energies. The value of $m$, in the exponent of current density in (15) for ac and dc MTF is found to be 7.5. The high values of $m$ compared to the usual value of 2, may be attributed to the large current densities used in our experiment. Similar large values of $m$ have been reported in other dc stress studies where high current densities were used [10]–[12] (although adjustment for self-heating in these experiments was already made). The equally high value of $m$ for dc MTF results verifies that large $m$ is not a result of ac stressing. This observation suggests the same $m$ may be used for both ac and dc lifetime prediction in our model. The ratio of MTF$_{ac}$/MTF$_{dc}$ versus current densities for stripe temperature $T = 250^\circ\text{C}$ is typically 1000, independent of $J$ as shown in Fig. 8. In other words, the $A_{dc}$ term in (15) is much larger ($\sim 1000$) than the $A_{ac}$ term in (7). Theoretically this suggests that $R_+ (\delta) \sim R_- (\delta)$ in (15) is much smaller than $R$ in (2), which we expect to be comparable to $R_+$ and $R_-$. The activation energy of ac stress lifetime was found from constant current stressing at several wafer chuck temperatures and two peak current densities of $3.5 \times 10^7$ and $5.0 \times 10^7 \text{ A/cm}^2$ (Fig. 9). Self-heating of the stripes at these two current densities raised stripe temperatures by $60^\circ\text{C}$ and $140^\circ\text{C}$, respectively. The activation energy found from the dc and ac MTF data was 0.33 eV. This is lower than the usually observed range of 0.4–0.55 eV. We speculate that the lower activation energy might be the result of surface diffusion dominating over grain boundary diffusion [13]. At temperatures larger than $300^\circ\text{C}$, the ac MTF data display a sharper reduction (Fig. 9). Possibly, a second temperature activated process is responsible for this effect.

In addition to using symmetrical ac ($J_+ = J_-$) waveforms in our experiment, we attempted several nonsymmetrical but pure ac (no dc component of current) rectangular waveforms (for example, see Fig. 3(b) and the MTF$_{ac}$ of test stripes stressed with these waveforms is plotted against $|J| |J|^{-m}$ using $m = 7.5$ in Fig. 10. The results demonstrate the applicability of (15) to nonsymmetrical pure ac waveforms. The MTF$_{ac}$ for the nonsymmetrical waveforms are about 3 times lower than predicted by (15), which we speculate is due to a weak dependence of $R_+$ and $R_-$ on current density. The thermal
transient effect cannot explain this discrepancy. For example, the average temperature for the data indicated by the inverted triangle in Fig. 10 ($J_1 = 2 \times 10^7$ A/cm$^2$, $J_2 = 4.1 \times 10^7$ A/cm$^2$) calculated from the root-mean-square current density is 295°C (worst case thermal cycling is 272°C in the positive half-cycle and 342°C in the negative half-cycle); the experimentally measured average temperature (which is used to adjust MTF) from resistance measurement is 343°C. Thus we would only overestimate the normalized MTF (at 250°C) if line temperature was actually lower than measured temperature.

The values of $A_{ac}(T)$ calculated from the pure ac data in Figs. 8 and 10 were plotted against the frequencies of the ac current in Fig. 11. $A_{ac}(T)$ is found by multiplying MTF$_{ac}$ by $|J|/|J|^{m-1}$ (15) using $m = 7.5$. Our model predicts that ac lifetime is insensitive to frequency, which is in agreement with the data plotted in Fig. 11 in the range from 35 kHz to 14 MHz. Recent ac and pulse dc studies by Maiz [14], Suehle and Schaft [15] also showed that MTF is independent of frequency from 1 kHz to 2 MHz. The frequency independence confirms the prediction by our model for $f > 1/\tau$ and $r$ is 1 ms or longer.

Upon examination of the failed test strips under an optical microscope, it was noted that in almost all of the ac cases, the open failure sites in the short 100-μm strips were found where the stripe joins the wider line (see Fig. 12). This observation can be explained by our assumption that ac failures occur at sites where there is the largest nonsymmetrical flow of vacancy flux. In this case, the imbalance of vacancy flux is caused by the geometry of the interconnect rather than the grain boundary arrangement.

In each test group stressed using nonsymmetrical ac waveforms, the open sites were preferentially located at the site that is the cathode side during the higher current half-cycles, i.e., if current from A to B is higher in magnitude than from B to A during the other half cycle, the open site is at point B. This can be explained as follows: because of the asymmetrical geometry, $R_1$ and $R_2$ at point A or B are different and when a nonsymmetrical waveform is applied the net flux divergence (from (14)) leads to the accumulation of vacancies at B and depletion of vacancies at A. The observation that open failures did not occur away from points A and B in our test lines suggests that the difference between $R_1$ and $R_2$ is probably the largest at point A and B (greater than that of any grain boundary points in the test line). The failure sites of test strips under symmetrical ac current stress were also preferentially, though to a lesser degree, located at one side of the bond pad, indicating a slight unintentional asymmetry of the current waveforms.

C. General AC

As noted in the previous discussion on pure ac lifetimes, the magnitudes of $R_1$ and $R_2$ are comparable to $R_1$,
and \( R_w - R_v \) is much smaller than \( R \). The comparison of \( A_{wT} (T) \) (in (15)) and \( A_{dc} (T) \) (in (9)) in Fig. 8 suggests that the ratio of \( (R_w - R_v)/2 \) to \( R \) is about 1000. Therefore, the second term in the brackets in (22) is usually negligible compared to the first term. This allowed us to write the approximate expression for (22) as

\[
TTF_{ac, dc} = \frac{A_{dc} (T)}{J} J \quad (23a)
\]

\[
= \frac{A_{dc} (T)}{J^2} \left( \frac{J}{J} \right) \quad (23b)
\]

Equation (23b) shows that the electromigration lifetime for the general case can be calculated using the average current \( J \) as in the pulse dc case but lifetime has to be derated by the factor \( J/|J| \). \( TTF_{ac, dc} \) is lower than \( TTF_{pulse, dc} \) for the same \( J \) because the vacancy concentration \( \bar{n} \) is proportional to the sum of the absolute current densities in both polarities \( |J| \) (19) and not the average current density \( J \).

Fig. 13 plots the MTF for ac waveforms with dc bias as a function of the derating factor \( J/|J| \). According to (23b), \( (MTF \times J^2)/A_{dc} \) gives the derating factor \( J/|J| \). This is verified in Fig. 13 for our data, as well as the Al-Si-Cu data from Hatanaka et al. [16]. If one assumes that \( MTF \propto 1/|J| \), the data in Fig. 13 should trace out a horizontal line at 1.0 independent of \( J/|J| \). That model would overestimate the lifetime for the ac waveform with dc bias.

In order to examine the validity of the approximation that leads to (23) specifically when the bidirectional ac waveforms approach the pure ac case, (22) is rewritten as

\[
TTF_{ac, dc} = \frac{A_{dc} (T)}{J} \left( \frac{J}{|J|} \right) \left( \frac{1}{1 + \frac{A_{dc} (T)}{A_{ac} (T)} \left( \frac{|J|}{J} - 1 \right)} \right) \quad (24a)
\]

or

\[
\frac{TTF_{ac, dc} \times |J|^2}{A_{dc} (T)} = \frac{J}{1 + \frac{A_{dc} (T)}{A_{ac} (T)} \left( \frac{|J|}{J} - 1 \right)} \quad (24b)
\]

Note that \( |J|^2 \) is not the same as \( J^2_{max} \).

In Fig. 14, the left-hand side of (24b) is plotted (using \( A_{ac}/A_{dc} = 1800 \)) as a function of \( J/|J| \). In the limit of pure ac waveform, i.e., \( J/|J| = 0 \), (23a) (indicated by the dashed line) and the average current density (indicated by the dotted line) predict infinite MTF. However, the complete model (24a) and our experimental data show that pure ac MTF is finite because \( A_{dc} \) is finite. Examining Fig. 14, we see that for \( J/|J| > 0.05 \), (23a) is a good approximation, i.e., lifetime for most ac waveforms with dc bias can be calculated assuming \( A_{dc} \approx \infty \). This approximation is good when \( A_{ac} \gg A_{dc} \). In Fig. 14, we also
plotted the root-mean-square current density model (i.e., MTF \( \propto 1/J_{\text{rms}}^m \)) for \( x = 0.4 \) and \( x = 0.8 \) (\( x \) is defined in the inset of Fig. 13). The predicted lifetimes for the current waveforms indicated in Fig. 14 using this model are in the area enclosed between these two lines. Thus the root-mean-square model is too pessimistic. On the other hand, the average current density model (the dotted line in Fig. 14) is too optimistic.

V. CONCLUSIONS

We have shown that if constant dc current stress lifetime is proportional to \( 1/J^m \), the lifetime under pulse dc current (arbitrary unidirectional waveform) stress, \( \text{MTF}_{\text{pulse}} \), is inversely proportional to \( J \cdot J^{-m} \). This equation is applicable to different shapes of unidirectional waveforms. For the important special case of \( m = 2 \), pulse dc stress lifetime is inversely proportional to the second power of the time-averaged current density. For pure ac current stress, we have found that the ac lifetime of interconnect \( \text{MTF}_{\text{ac}} \) is typically much larger (\( \sim 1000 \)) than the dc lifetime because of the heating effect by the two opposing flows of vacancy flux. The magnitude of this enhancement factor for \( \text{MTF}_{\text{ac}} \) is insensitive to current densities, waveforms, and frequencies but depends on the grain microstructure and the geometry of the interconnect. In our study, the latter effect seems to be the dominant factor in causing failure in short lines (100 \( \mu \text{m} \)) while the former dominates in longer (800 \( \mu \text{m} \)) lines. The pure ac lifetime for interconnect was shown to fit Black’s equation for dc electromigration failure, provided we replace \( J^m \) with \( \left| J \right| \cdot \left| J \right|^{-m} \), and \( A_{\text{ac}}(T) \) with \( A_{\text{ac}}(T) \). We have found that the exponent \( m \) and the activation energy \( E_a \), up to 300°C are the same in the dc (7) and ac electromigration equation (15). For the case of a general bidirectional waveform, lifetime can be calculated from (21) which is valid for an arbitrary waveform. The two quantities needed for the calculation are the average density \( J \) and the average for the absolute current density \( \left| J \right| \). For most bidirectional waveforms with dc bias, TTF can be calculated using the average current density \( J \) in the usual Black’s equation, but the TTF is denoted by the factor \( J/\left| J \right| \) (23b). In the limit of small dc bias or pure ac current waveforms, the full equation (24) will have to be used. We have also shown that under bidirectional current conditions, the average current density model (MTF \( \propto 1/J_{\text{rms}}^m \)) will give a lifetime projection that is too optimistic while the root-mean-square model (MTF \( \propto 1/J_{\text{rms}}^m \)) will give a pessimistic prediction.

While we have only studied Al–Si samples, the vacancy relaxation model is believed to be applicable to other metals. The only available ac data for Al–Si–Cu [16] were found to agree with the model prediction in Figs. 13 and 14. Self-heating under pulse operation merits consideration too. While it is straightforward to estimate the time average of temperature rise due to self-heating (from \( J_{\text{rms}}^m \) or \( J^m \)), it is more difficult to include the temperature excursions around the average temperature in TTF calculations. Fortunately, it can be shown [17] that these temperature excursions indeed have negligible effect on Al interconnect TTF in the usual range of average current density (\( \sim 1 \times 10^8 \text{A/cm}^2 \)), frequency (\( > 10 \text{MHz} \)), and duty factor (\( > 0.1 \% \)).

Using this model, one can estimate the lifetime for arbitrary waveforms after characterizing the dc lifetime and perhaps the pure ac lifetime at some conventional frequency such as 10 kHz.

REFERENCES


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