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<td>Author(s)</td>
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<td>Date</td>
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Requirement for Accurate Interconnect Temperature Measurement for Electromigration Test

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Abstract—In this work, we show accurate temperature measurement is important in electromigration (EM) test as it can affect the measured activation energy EA and current density exponent n. The deviation of measured EA and n due to the interconnect temperature variations are derived analytically and illustrated in Cu/low-k interconnects using finite element analysis (FEA) under typical experimental conditions. The derived formulations are verified by our previous experimental works.

I. INTRODUCTION

With continuous scaling of device dimensions, electromigration (EM) remains to be a severe reliability concern for integrated circuit (IC) interconnects [1]. The influence of the current density j and metal line temperature T on the median time to failure (MTF) \( t_{50} \) is described by the Black’s equation [2],

\[
t_{50} = A \cdot j^{-n} \cdot e^{E_A/K_BT}
\]

where \( E_A \) is the activation energy, \( n \) is the current density exponent, \( A \) is a parameter sensitive to the fabrication process and the geometry of the interconnect, and \( K_BT \) has the usual meaning. It is critical to measure the metal line temperature accurately as it can affect the experimentally determined \( E_A \) and \( n \) as shown in (1).

The interconnect temperature increment due to Joule heating is usually estimated by utilizing the temperature coefficient of resistivity (TCR) of the metallization in EM test [3]. In practice, the actual interconnect temperature can deviate from the estimated interconnect temperature due to the oven temperature variations, individual interconnect resistance variations, the accuracy of TCR, etc. With more severe Joule heating expected in future Cu/low-k interconnects, the sample resistance variations are becoming more important since Joule heating is dependent on the sample resistance, resulting in higher temperature variations in interconnects.

In this work, we show the importance of accurate interconnect temperature measurement in EM test as the variations of the interconnect temperatures can lead to the variations of experimentally determined \( E_A \) and \( n \) although the actual \( E_A \) and \( n \) do not change. The Joule heating effect and the associated temperature variation are estimated using finite element analysis (FEA) under typical experimental conditions for Cu/low-k interconnects. The variations of \( E_A \) and \( n \) due to interconnect temperature variations are derived analytically so that they can be re-estimated once the temperature variations are known. The variations of \( E_A \) and \( n \) are found to be dependent on the temperature variation, EM test temperature, and actual activation energy \( E_A \).

II. TEMPERATURE VARIATIONS IN INTERCONNECTS

Interconnect temperature in oven EM test can be expressed as

\[
T = T_{oven} + \Delta T_{joule}
\]

where \( T_{oven} \) is the oven temperature and \( \Delta T_{joule} \) is the temperature increment due to Joule heating. For typical high temperature oven used in EM test,

\[
T_{oven} = T_{set} + \Delta T_{oven}
\]

where \( T_{set} \) is the oven temperature setting and \( \Delta T_{oven} \) is the temperature variation of the oven. Typical oven shows 1% uniformity in the spatial temperature distribution as in the specification for Blue M™ oven. Therefore, \( \Delta T_{oven} = \pm 0.01 \cdot T_{set} \).

Temperature rise due to Joule heating is formulated as [3]

\[
\Delta T_{joule} = \frac{\Delta R}{TCR \cdot R_0}
\]

In (4), \( \Delta R \) is the resistance difference between the Joule heated sample resistance \( R_j \) and non-Joule heated sample resistance \( R_0 \). \( R_0 \) is the sample resistance at 0 °C and TCR is also referenced at 0 °C. It is noted that \( \Delta R \) is dependent on stress current, non-Joule heated sample resistance and TCR. Depending on the manufacturing process, the initial sample resistance can have a variations up to 10% [4], leading to different \( \Delta T_{joule} \) among different samples. Besides that, TCR is also different for different samples as it is dependent on the microstructure of the sample [5]. For Cu interconnect, constant TCR cannot be used because Cu resistivity is no longer linearly dependent on temperature above 200 °C [6], and EM test for Cu interconnect is usually performed around 300 °C. All the above-mentioned facts result in the fluctuations of \( \Delta T_{joule} \), especially in the presence of severe Joule heating.
To simplify the analysis, we only consider the fluctuation of resistance among the samples and temperature variation in the oven in this work. In fact, this is an optimistic assumption because the TCR variations shall further increase the interconnect temperature variations. We denote the variation of interconnect temperature $T$ in (2) as $\varepsilon$. From (2) and (3),

$$\varepsilon = \frac{\Delta T_{\text{oven}}}{\Delta R_{\text{oven}}} \times \Delta R = \Delta T_{\text{oven}} + \varepsilon_{\text{Joule}}$$

(5)

$\varepsilon_{\text{Joule}}$ in (5) is the variation of the temperature increment ($\Delta T_{\text{oven}}$) under Joule heating effect which is due to the variation of sample resistance and it is estimated by FEA as shown below.

Joule heating effect is estimated by the coupled field electrical-thermal analysis using finite element software ANYSSTM for a typical Cu/low-k interconnect. The finite element model is shown in Fig. 1 with Ta diffusion barrier and SiN cap layer included. The dimensions of line width and line thickness are 0.28 and 0.35 $\mu$m respectively. Via height is 0.7 $\mu$m. Low-k material carbon-doped oxide (CDO) is chosen as the dielectrics in this work. The material properties are taken from [7]. In the analysis, the substrate bottom surface is kept at constant EM test temperature with a pre-determined current density applied to the interconnect. The simulation results are summarized in Table I.

<table>
<thead>
<tr>
<th>Current density (MA/cm$^2$)</th>
<th>Temperature ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>0.01</td>
<td>100</td>
</tr>
<tr>
<td>0.5</td>
<td>100.55</td>
</tr>
<tr>
<td>1</td>
<td>102.23</td>
</tr>
<tr>
<td>2</td>
<td>109.08</td>
</tr>
<tr>
<td>4</td>
<td>139.61</td>
</tr>
<tr>
<td>6</td>
<td>191.07</td>
</tr>
</tbody>
</table>

Table I. JOULE HEATING EFFECT AT DIFFERENT TEST TEMPERATURES AND CURRENT DENSITIES FOR CU/CDO INTERCONNECTS

![Fig 1: Finite element model for Joule heating effect simulation.](image)

From Table I, at a test temperature of 300 $^\circ$C and current density of 4 MA/cm$^2$, the temperature increment is 63.42 $^\circ$C, close to the 65 $^\circ$C as reported by Wu et al. [8] for the same stress conditions for low-k interconnect. For the same test temperatures, the temperature increment is proportional to the square of current density, which shows the temperature increment is indeed due to the Joule heating effect. It is also noted that under the same current density, the temperature increment is higher for higher test temperature.

For $\varepsilon$ in (5), $\Delta T_{\text{oven}}$ is dependent on the oven temperature. The variation of temperature increment under Joule heating $\varepsilon_{\text{Joule}}$ is estimated by FEA. For illustration, we choose a typical stress current of 4 MA/cm$^2$ and a typical 10% variation in interconnect resistance [4]. The change of interconnect resistance is computed by changing Cu resistivity values in the material library in the FEA simulations. $\varepsilon_{\text{Joule}}$ in (5) under a combination of different oven temperatures and resistivity is simulated and the results are summarized in Table II. It is noted that $\varepsilon_{\text{Joule}}$ is dependent on the resistivity variation and the Joule heating effect. Copper resistivity variation due to non-uniform temperature is taken into account using TCR in the simulation. The temperature variation will be much lower if a smaller current density is used in the EM test.

As shown in Table II, lower Cu resistivity leads to a negative temperature variation since the generated Joule heat is linearly dependent on the resistivity. Table II, together with $\Delta T_{\text{oven}}$, will be used for the numerical calculations in the following sections.

### III. ACTIVATION ENERGY VARIATIONS

Activation energy $E_A$ of EM is often estimated as the slope of $t_{50}$ versus $1/kBT$ in the lifetime plot. If the line fitting is based on the inaccurate interconnect temperature, the estimated $E_A$ can be different from the actual $E_A$. It remains unknown how the variation of interconnect temperature affects the estimated $E_A$.

The derived correction function is shown in (6),

$$E_A = E_A \left[ \frac{1 - \varepsilon}{T} \right]$$

(6)

In (6), $E_A$ is the actual activation energy which is independent on test conditions, and $E_A\varepsilon$ is the experimentally determine activation energy. For Cu/low-k interconnect with an $E_A$ of 0.9 eV for interfacial diffusion [9], with the estimated $\varepsilon$ and $T$ in Table II, the experimentally determined $E_A\varepsilon$ under different oven temperature and Cu resistivity is shown in Fig. 2.

For interconnect resistivity at 0.9$\rho_{\text{Cu}}$, the temperature variation is negative as shown in Table II. In other words, the estimated interconnect temperature is lower than the actual interconnect temperature and this results in slightly higher estimated activation energy than the actual $E_A$ of 0.9 eV for interfacial diffusion. With higher interconnect resistivity, the estimated $E_A$ decreases. The variation of estimated $E_A$ on oven temperature is small due to the low variation of oven temperature in EM test. For the same interconnect resistivity, higher oven temperature is associated with higher $E_A$ variation as shown in Fig. 2, but its effect is negligible.
Table II: THE TEMPERATURE INCREMENT UNDER JOULE HEATING EFFECT AND ITS VARIATIONS AT DIFFERENT OVEN TEMPERATURE AND INTERCONNECT RESISTIVITY. THE SIMULATION IS BASED ON CU/CDO INTERCONNECT WITH A CURRENT DENSITY OF 4 MA/CM².

<table>
<thead>
<tr>
<th>Oven temperature (°C)</th>
<th>ΔT joule in (1)</th>
<th>ε joule at 0.9ρ₀ (°C)</th>
<th>ε joule at 0.95ρ₀ (°C)</th>
<th>ε joule at ρ₀ (°C)</th>
<th>ε joule at 1.05ρ₀ (°C)</th>
<th>ε joule at 1.1ρ₀ (°C)</th>
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<tbody>
<tr>
<td>150.00</td>
<td>45.57</td>
<td>-6.43</td>
<td>-3.16</td>
<td>0.00</td>
<td>3.48</td>
<td>7.08</td>
</tr>
<tr>
<td>200.00</td>
<td>51.52</td>
<td>-7.19</td>
<td>-3.53</td>
<td>0.00</td>
<td>3.90</td>
<td>7.92</td>
</tr>
<tr>
<td>250.00</td>
<td>57.47</td>
<td>-7.95</td>
<td>-3.91</td>
<td>0.00</td>
<td>4.31</td>
<td>8.75</td>
</tr>
<tr>
<td>300.00</td>
<td>63.42</td>
<td>-8.71</td>
<td>-4.28</td>
<td>0.00</td>
<td>4.72</td>
<td>9.59</td>
</tr>
<tr>
<td>350.00</td>
<td>69.55</td>
<td>-9.47</td>
<td>-4.65</td>
<td>0.00</td>
<td>5.13</td>
<td>10.43</td>
</tr>
<tr>
<td>400.00</td>
<td>75.67</td>
<td>-10.23</td>
<td>-5.03</td>
<td>0.00</td>
<td>5.54</td>
<td>11.26</td>
</tr>
</tbody>
</table>

Fig. 2: The variation of Ea due to the variation of sample resistance and oven temperature. Actual Ea is assumed to be at 0.9 eV.

The variation of Ea in Fig. 2 shall lead to large variations of t₅₀ if these Eₐ is used in the Black’s equation for lifetime extrapolation. The variation of t₅₀ due to the variation of Eₐ is shown in Fig. 3. The variation of t₅₀ is much higher than that of Eₐ since t₅₀ is exponentially dependent on Eₐ. For the same interconnect resistivity, higher oven temperature is associated with lower t₅₀ variation as shown in Fig. 3.

Equation (6) is validated by our previous experimental work [4]. The reported variation of Eₐ (delta Eₐ) is within 0.01~0.02 eV with ΔT=13.83 °C, T=275 °C, Eₐ is within 0.85~0.88 eV. Using (6), the variation Eₐ is estimated to be ~0.02 eV, close to the experimentally reported value.

IV. CURRENT DENSITY EXPONENT VARIATIONS

Current density exponent n is an indication of EM failure process. It is commonly accepted that n=2 is for void nucleation limited failure and n=1 is for void growth limited failure [10]. However, n can be larger than 2 under Joule heating effect [11].

Consider EM test at two different current densities, j₁ and j₂ (j₁<j₂) with test temperature T. The temperature increment due to Joule heating is denoted as ΔT₁ and ΔT₂.

\[ t'_50 = A \cdot j_1^{-n'} \cdot e^{E_A / K_A T} \]  
\[ t''_50 = A \cdot j_2^{-n'} \cdot e^{E_A / K_A T} \]  

where \( n' \) is the experimentally determined current density exponent excluding Joule heating effect. Combine (7) and (8),

\[ \ln t'_50 - \ln t''_50 = -n' \cdot (\ln j_1 - \ln j_2) \]  

(9)

By considering Joule heating effect,

\[ t'_50 = A \cdot j_1^{-n} \cdot e^{E_A / K_A (T+\Delta T_1)} \]  
\[ t''_50 = A \cdot j_2^{-n} \cdot e^{E_A / K_A (T+\Delta T_2)} \]  

(10) (11)

where \( n \) is the Joule heating effect corrected current density exponent. Combine (10) and (11),

\[ \ln t'_50 - \ln t''_50 = -n \cdot (\ln j_1 - \ln j_2) \cdot e^{E_A / K_A (T+\Delta T_1)} \cdot \left( 1 - \frac{1}{T+\Delta T_1} \right) \]  

(12)

Combine (9) and (12), we have

\[ n = n + \frac{E_A (\Delta T_2 - \Delta T_1)}{K_A (T+\Delta T_1)(T+\Delta T_2)(\ln j_1 - \ln j_2)} - n \]  

(13)

The current density exponent correction factor Δn in (13) can be further simplified from the intrinsic nature of Joule heating. The temperature increment can be written as \( \Delta T = K_A j^2 \).

Therefore, \( \Delta n \) can be re-written as
resistivity as shown in Fig. 4. The estimated other words, the value of \( n \) will be seemingly temperature and
\[
\Delta n = \frac{E_A}{K_B} \left( \frac{K_j^2 - K_{j2}}{(T + K_j^2) (T + K_{j2})} \left( \ln j_1 - \ln j_2 \right) \right)
\]
\[
= \frac{E_A}{K_B} \frac{K_j}{(T + K_j^2)} \left( \frac{1}{j_1} - \frac{1}{j_2} \right)
\]

To obtain \( \Delta n \) as a function of \( j \), we take the limit of \( (j_1 - j_2)/j_1 = 0 \), and we have
\[
\Delta n = \lim_{(j_1/j_2)\to 0} \frac{E_A}{K_B} \frac{K_j}{(T + K_j^2)^2} \left( \ln j_1 - \ln j_2 \right)
\]
\[
\Delta n = \frac{2 \cdot E_A}{K_B} \frac{K_j}{(T + K_j^2)^2} \left( \ln j_1 - \ln j_2 \right)
\]

The correction function \( \Delta n \) due to temperature variation \( \varepsilon \) is shown in (16). The current density exponent variation factor \( \Delta n \) is dependent on the amount of temperature variation \( \varepsilon \), test temperature \( T \), as well as actual activation energy \( E_A \). In other words, the value of \( n \) will be seemingly temperature and current density dependent experimentally.

With the previous determined \( E_A \) in Fig. 2 and temperature variation in Table II, \( \Delta n \) is plotted with the variation of resistivity as shown in Fig. 4. The estimated \( \Delta n \) is less than one for the temperature variation considered in this work.

Using experimental data from our previous work, \( E_A = 0.87 \text{ eV}, \varepsilon = 3 \text{ °C}, T = 300 \text{ °C} \), substitute into (16), \( \Delta n \) is estimated to be 0.18, close to the experimentally corrected \( n \) of 0.1 and 0.2 for narrow and wide interconnects [4]. Therefore, the estimation from (16) is consistent with the experimental values.

V. CONCLUSIONS

In this work, the formulations for the variation of \( E_A \) and \( n \) are derived analytically and verified through our recent experimental work. As the temperature variation in interconnect is becoming more important in EM test in future low-k interconnects, the results in this work can provide a quick and accurate assessment on the variation of EM parameters in high current EM test.


