Electromigration Risk Assessment and Circuit Optimization using Innovative Multiphysics Modeling

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Abstract
With smaller and denser transistors, the physical flow of electrons may inhibit the performance of the device over time by forming voids and cracks at interconnects due to Electro-Migration (EM). Circuit designs that fail to meet EM specifications may lead to catastrophic failures and SI/PI performance degradation. One way of mitigating EM is to use multiple vias between layers of copper traces to reduce the current crowding effect. However, the quantities of vias may affect the current density and current redistribution inside critical joints. Current studies mainly focus on predicting the EM time-to-failure (TTF) based on the empirical Black's equation. However, this method may not give enough insights about void formation and crack propagation and reflects the current redistribution that could impact the TTF. In this study, we compared the EM lifetime of Ball Grid Array (BGA) test vehicles with different structural designs and developed a methodology to consider the diffusion of atoms in solder joints based on Multiphysics field migration to study the current redistribution influence of vias. Moreover, crack propagation was also simulated to understand the failure mechanism. BGA traces without vias and with 8 vias are stressed under 5A, 7A, and 9A at 150C to compare the EM performance. Moreover, each test structure is manufactured with two different surface finishes: A and B. Based on the experimental results, Finite Element Analysis (FEA) simulations based on Atom Flux Divergence (AFD) were performed to compare with the experiment results. It was found that the current crowding effect could be significantly reduced by 8 vias compared to daisy chained traces. The study shows better EM resistance with 8 and 4 vias than no-via traces and helps predict the EM life of different structures to provide guidance for design optimization.

Key words
Electromigration, reliability, Multiphysics, Finite Element Analysis, circuit optimization

I. Introduction
With the development and minimization trend of electronic components and products, microelectronic interconnections have been designed with continuously decreasing scale and pitch [1]. With each silicon node, current delivery to the conductors is becoming increasingly higher and generates elevated temperature due to joule heating [2]. Electromigration (EM) is one of the most critical failures that need to be considered for structures under higher current input. The physical flow of electrons will inhibit the performance of devices and lead to voids and open circuitry due to the electron momentum transferred to atoms, as shown in Fig. 1 [3].

Many studies have been done to evaluate the electromigration risk, the most commonly used empirical equation to assess the time-to-failure (TTF) is Black’s equation.

\[
MTTF = \frac{A}{j^m} \exp \left( \frac{E_A}{k_B T} \right)
\]

(1)

Where \( j \) is the current density, \( T \) is the local temperature. A
is a constant, \( E_a \) is activation energy and \( K_b \) is Boltzmann’s constant \([4]\). The electromigration resistance is related to the thermal-electric input. However, electromigration in real life is a Multiphysics diffusion phenomenon that couples thermal electrical as well as stress migration \([5]\). Moreover, the empirical equation may not be capable of characterizing the current crowding effects and thus having limits in providing more insights for the failure mechanism.

**II. Methodology**

In reality, the atoms are driven under the electron winds during the EM process, where the near upwind side voids will form and downwind side hillocks will accumulate. The phenomenon involves different physics fields including electron wind migration, temperature gradient migration, and stress gradient migration. According to AFD theory, the coupling diffusion flux is the superposition of atom flux under different physics fields. The different migration flux under different driven forces is listed \([9-11]\).

**A. Electron Wind Migration**

The atoms moving under the electric field will collide with electrons and cause drastic momentum exchange. The driving force can be obtained as shown:

\[
\vec{F}_{ew} = \vec{F}_{direct} + \vec{F}_{wind} = Z^*epj
\]

(2)

Where \( \vec{F}_{direct} \) is the Coulomb force and \( \vec{F}_{wind} \) is the electron wind, \( \vec{F}_{ew} \) is the total force, \( Z^* \) is the effective charge number, \( \rho \) is the resistivity and \( j \) is the local current density. The electron wind caused migration flux can be described as:

\[
\vec{J}_{ew} = \frac{e}{k_B T}D_0 \exp \left(- \frac{E_a}{k_B T}\right) z^* j \rho
\]

(3)

Where \( \alpha \) is the temperature coefficient of resistivity, \( \rho_0 \) is the resistivity at \( T_0 \), \( C \) is the atomic concentration where atomic volume \( \Omega = 1/C \), the atomic volume is a very small value thus the second term of \( \text{div}(\vec{J}_{ew}) \cdot \frac{1}{c^2}\vec{J}_{ew}\nabla C \), can be simplified.

**B. Thermal Migration**

Joule heating will be generated when the current passes through the conductors. The different heat dissipation at different structure locations will introduce temperature variance. Such a temperature gradient will drive atoms to move from areas that have a higher temperature to areas that have a lower temperature. The driving force of thermal migration can be derived as:

\[
\vec{F}_{th} = Q^* \nabla T
\]

(4)

Where force is related to the gradient of temperature and \( Q^* \) is the heat of transport. The thermal migration flux can be described as:

\[
\vec{J}_{th} = \frac{eC}{k_B T} D_0 \exp \left(- \frac{E_a}{k_B T}\right) Q^* \nabla T
\]

(5)

And the flux divergence can be calculated as shown below:

\[
\text{div}(\vec{J}_{th}) = \left( \frac{E_a}{k_B T} - \frac{3}{2} + \alpha \frac{\partial \rho}{\partial T} \right) \vec{J}_{th} \nabla T + \frac{CQ^*D_0}{k_B T} j^2 \rho^2 e^2 + \frac{1}{c^2}\vec{J}_{th} \nabla C
\]

(6)

The last term \( \frac{1}{c^2}\vec{J}_{th} \nabla C \) can be similarly simplified.

**C. Stress Migration**

The driving force of stress gradient can be written as:

\[
\vec{F}_{ew} = \nabla \sigma_H
\]

(7)

Where the \( \sigma_H \) is the hydrostatic stress. The stress migration flux can be shown below:

\[
\vec{J}_{\sigma} = \frac{eC}{k_B T} D_0 \exp \left(- \frac{E_a}{k_B T}\right) \nabla \sigma_H
\]

(8)

The flux divergence can be described as:
\[ \text{div}(\mathbf{J}) = \left( \frac{E_a}{k_B T} - \frac{1}{\tau} \right) \mathbf{J} \mathbf{\nabla}T + \frac{C}{k_B T} \text{div}(\nabla \sigma_H) \]

(9)

In summary, the governing equation to model the Multiphysics diffusion can be summarized as:

\[ J_{\text{total}} = \frac{\kappa}{k_B T} D_0 \exp \left(-\frac{E_a}{k_B T}\right) \left( eZ^\prime j \rho + Q^\prime \frac{\mathbf{v} \cdot \mathbf{\nabla} T}{T} + \Omega \nabla \sigma_H \right) \]

(10)

Based on the governing equation describing the atom behavior during electromigration, the vacancy/atom concentration of elements can be obtained by modeling. The flow chart of conducting the Multiphysics modeling is shown in Fig. 2. In the first step, only electro-thermal analysis is performed. The objective of the static analysis is to obtain the initial temperature distribution and apply it as the input for transient analysis. Based on the available temperature, the Multiphysics modeling is performed where the element vacancy concentration is used as a criterion to execute void initiation in the loop. Once the vacancy concentration of a certain element reaches the threshold, we consider the element has evolved into a void so the element is killed and the geometry of the model will be updated. Meanwhile, the voltage of the conductive parts, which represents the resistance increase of the structure, is also examined. Once the structure reaches a 15% resistance increase, the simulation will stop and be considered a failure of the entire structure.

The above process brings another advantage of the modeling methodology. Compared to empirical Black’s equation estimation that has a fixed resistance increase criterion, the criterion of resistance increase can be adjusted flexibly according to the actual experimental criterion.

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**Table I. Comparison of different approaches**

<table>
<thead>
<tr>
<th>Physics field</th>
<th>Empirical Black’s equation</th>
<th>Proposed FEM approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure criterion</td>
<td>Tuned for fixed condition</td>
<td>Flexible for different resistance criterion</td>
</tr>
<tr>
<td>Failure mechanism simulation</td>
<td>No</td>
<td>Simulate void initiation and crack propagation</td>
</tr>
<tr>
<td>Design rule spec setup</td>
<td>Limited</td>
<td>More insights</td>
</tr>
</tbody>
</table>

**Table II. Material properties for EM**

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Cu</th>
<th>SAC305</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structural</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulus (MPa)</td>
<td>127e3</td>
<td>26.2e3</td>
</tr>
<tr>
<td>CTE (ppm/K)</td>
<td>17.1</td>
<td>23</td>
</tr>
<tr>
<td>ν</td>
<td>0.31</td>
<td>0.35</td>
</tr>
<tr>
<td>Atomic volume (m³)</td>
<td>1.182e-29</td>
<td>2.71e-29</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity k (W/m · K)</td>
<td>393</td>
<td>57</td>
</tr>
<tr>
<td>Specific heat (J/kg · K)</td>
<td>385.2</td>
<td>219</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>8900</td>
<td>7390</td>
</tr>
<tr>
<td>Heat of transport (eV)</td>
<td>0.3121</td>
<td>0.0094</td>
</tr>
<tr>
<td><strong>Electric</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistivity ρ (Ohm · m)</td>
<td>2.52e-8</td>
<td>18.1e-8</td>
</tr>
</tbody>
</table>
III. Results and Discussion

After static thermal electric analysis, the initial temperature and current distribution can be obtained. The film coefficient is correlated as 1000W/m²·C for the half symmetric model. As shown in Fig. 5(a), when both structures are under the 5A and 150C condition, the joule heating effect of no via structures and structures with vias is compared. In previous studies, it is found that using single via design may cause significant Joule heating and result in earlier failure of the structure. However, in this study, although both structures show temperature increase compared to ambient temperature, the structure without vias has similar highest temperature to the structure that has 8 vias. The multiple vias help share the current loading so that each via has a lower current density. It can be validated in Fig. 5(c), that the maximum current density of the victim solder of structure without vias is 1.8e4 A/cm². Due to the current crowding effect, the highest current density is located at the entrance location of the current. However, for the structure with 8 vias, the maximum current density is much smaller, around 0.6e4 A/cm². The current crowding effect still exists in the via structure, the current density is the highest underneath the via near the current entrance location, such via can be considered as a critical via. The current density reduces in other vias that is far from the critical via. The temperature can be applied into the transient Multiphysics analysis, with the diffusion proceeds, the element vacancy concentration will increase and generate cracks. As shown in Fig. 6, voids will form and further propagate due to the increase of vacancy concentration. Meanwhile the crack will intensify the current crowding and cause the further increase of maximum current density, which leads to final failure. The void initiates near the location that has maximum current density, for structure without vias, it forms at the solder edge and propagates towards the other side. However, for a structure that has 8 vias, the void appears underneath the critical via and expands gradually in other directions. The variance of failure mechanism in modeling can be verified. In Fig. 7(a), the test vehicle without vias has the interfacial voids initiated at the edge and in Fig. 7(b) the cracks expand along both directions around the critical via in the test vehicle with 8 vias. In both structures voids generate at the upwind side of the electron wind. Moreover, the resistance increase in modeling is compared with the experimental data, which shows a similar increase in resistance when crack propagates along the interface, as shown in Fig. 8.

In order to correlate the modeling TTF to actual experiment results, the vacancy concentration threshold needs to be tuned. Moreover, it can be used as the parameter to
characterize the diffusion barrier effect [13] when the test structure has different surface finishes. In the modeling we describe the critical concentration as:

\[ C_{critical} = A \cdot f(j) \cdot f(T) \]  
(11)

Where A is a constant, f(j) is a function related to the feeding current, since the IMC growth is related to the current value [14], the A • f(j) can be expressed as \( A \cdot j^n \) where n is the current exponent and this term can be used to characterize the diffusion influence introduced by the surface finish. f(T) is a function related to temperature, as shown in Fig. 9, the failure criterion is adjusted during the modeling because when the void is generated, the local temperature will increase, thus the adjustment of f(T) can be written in the form of updated critical concentration [15]:

\[ f(T) = C_{initial} \cdot \exp \left( -\frac{1}{k_B T_{new}} \right) / \exp \left( -\frac{1}{k_B T_{initial}} \right) \]  
(12)

Where the \( T_{new} \) is the increased temperature, \( C_{initial} \) and \( T_{initial} \) is the initial vacancy concentration and initial local temperature.

As a result, we are able to correlate the critical vacancy concentration threshold parameters to the experimental testing TTF data. As shown in Table. III, by correlating the experimental data of structures without vias under 5A and 9A. The structure with vias shows no failure till 2000 hours so the parameters are fitted with the structure without vias. The constant A and n can be fitted for A and B surface finish. For A, \( C_{critical} \) can be expressed as:
The critical concentration for B can be fitted as:

\[ C_{\text{critical}} = 2.39 \cdot j^{-0.14} \cdot f(T) \]  
(14)

Table. III. Experiment and modeling TTF of two surface finishes in structures without vias

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Experiment TTF (h)</th>
<th>Modeling TTF (h)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1483</td>
<td>1400</td>
<td>12%</td>
</tr>
<tr>
<td>7</td>
<td>214</td>
<td>200</td>
<td>6%</td>
</tr>
<tr>
<td>9</td>
<td>83</td>
<td>100</td>
<td>20%</td>
</tr>
</tbody>
</table>

IV. Modeling Analysis: Design Optimization

With the above methodology, we are capable of performing analysis and predicting the EM performance of different structures. The structure with 8 vias shows no failure till 2000 hours no matter if it has surface finish A or B plating, and the simulation further validates that the TTF of structures with 8 vias can endure more than 3000 hours. However, although multiple vias can help increase the EM performance, implementing vias during manufacturing will increase the cost [16]. In Fig. 10, a four via structure is designed to reduce the cost compared to the eight via structure. Based on the modeling results, it shows a similar failure mechanism that voids initiates underneath the critical via. The TTF of 4 via structure with surface A is 2400 hours, which is worse than the 8via case but still shows improvement compared to no via case.
V. Conclusion

In this study, an innovative FEM methodology is proposed to not only simulate the crack propagation behavior of conductor under current loading but also introduce the critical vacancy concentration threshold to characterize the diffusive influence of IMC growth and surface finish. Two different structures with surface finish A and B are compared and correlate the modeling results. Different surface finish plating results are correlated with the testing data at 5A and 9A. With the fitted results, TTF at 7A can be predicted and validated.

Based on the simulation results, the current crowding effect could be significantly reduced by 8 vias, which is consistent with the experiment data that the structures with 8 vias show longer TTF than the ones without vias. We introduced a void nucleation threshold in FEA to reflect the impact from surface finishing as a diffusion barrier. The surface finish B has a higher void nucleation threshold due to the Nickel content. The influence of surface finish is also introduced to simulate the diffusion barrier effect because of chemical composition difference. With the proposed model, this study further investigates the feasibility to reduce the contact window area by changing the 8 vias to 4 vias while still meeting the EM specification requirement as a cost-effective tradeoff. The study shows better EM resistance with 8 and 4 vias than no-via traces and helps predict the EM life of different structures to provide guidance for design optimization.

References


