Numerical Simulations of Electromigration and Stressmigration Driven Void Evolution in Solder Interconnects

Understanding the effect of high current density on void formation and growth and relating the size of the void to the resulting electrical/mechanical failure is a critical need at the present time to ensure reliable functioning of flip-chip packages. In general, toward this end, the modeling and simulation of geometrical evolution of current induced voids have been relatively few. Simulations considering the coupled effects of mass transport through mechanisms of surface and bulk diffusion under the influence of electrical, thermal, and stress fields in solder joints leading to eventual electromigration failure do not appear to be common. In this study, we develop a phase field model for the evolution of voids under electrical, thermal, and stress fields in a flip-chip solder interconnect. We derive the equations of motion for the void accounting for energetic contributions from the active factors of surface energy, stress, and electric potential, considering both surface diffusion and transfer of the material through the bulk of the material. We describe the implementation of this model using a finite element code written in the Python language, coupled with a commercial finite element solver from which we obtain the electrical, thermal, and stress fields driving the void motion. We demonstrate the implemented methodology through simulations of void evolution in flip-chip solder joints under the effects of mechanical/electrical fields and surface/bulk diffusion. [DOI: 10.1115/1.4006707]

Introduction

The decrease in the size of the flip-chip solder joints has resulted in a corresponding increase in the current densities prevalent in the joints. This has led to an increase in the importance of failure due to electromigration in flip-chip solder joints [1]. Electromigration is caused by the momentum exchange between electrons and ions that forces material diffusion in the direction of electron flow. This leads to the formation of voids near the cathode that might lead to an open failure. There is also the likelihood of the formation of hillocks at the anode that might cause a shorting failure. The formation and motion of the voids are also driven by the existence of stress and temperature gradients. A unique problem that occurs in solder joints is the failure due to current crowding. The current density in the signal trace leading up to the joint is significantly higher than the current density in the solder joint. At the interface between the two, there is a region of the solder joint, where the current density is an order of magnitude higher than the rest of the joint ($\approx 10^5$ A cm$^{-2}$ at the entrance versus $\approx 10^4$ A cm$^{-2}$ near the middle [1]). This causes the void formation to be very rapid near the current crowding region (see Fig. 1).

The computational simulation of the formation and propagation of voids in solder is a challenging problem. There are a multitude of interacting physical effects such as the electrical, thermal, and stress fields that determine the void shape and its rate of evolution. A significant attempt at modeling electromigration in solder joints has been through the use of damage mechanics to simulate the loss in load-bearing capacity of the solder joints [2,3]. These models enable one to find locations of void formation and in modeling the motion of very small, diffuse, voids, whose boundaries are not explicitly captured. These methods do not explicitly model the geometry of the voids, but infer the effects of the formed voids through the damage they cause to the load-bearing capacity. However, geometrically speaking, the removal of material from a region results in the formation of new surfaces. Further, energy-wise, every new surface formation has an associated surface energy cost [4] that needs to be accounted for in any complete simulation of the motion of voids.

An alternative approach to modeling electromigration has been to capture the divergence of atomic flux directly within a finite element code [5,6]. In these approaches, the modeling of motion and growth of larger voids appear to rely mostly on element deletion schemes, which approximate the boundary of the voids accurately in the limit of mesh refinement [6]. Furthermore, these methods also ignore the surface energy associated with void boundaries or surface diffusion along the void boundary, and rely on the underlying physics of electromigration being captured entirely in the bulk through the divergence of flux.

As the voids evolve, the underlying geometrical domain on which the boundary value problems are solved changes. One way to handle this is by explicitly tracking the motion of the void surface. There are very few attempts in the current literature aimed at explicitly modeling the evolution of electromigration-induced voids [7,8]. The main challenge with explicit geometry tracking methods is handling the constantly changing problem domain, which necessitates remeshing with a mesh-based numerical scheme such as the finite element method. Also, in an explicit scheme, the processes that cause topological changes such as the splitting of the voids require special treatment and are in general very difficult to model numerically.

An alternative to this method is to use a phase field model for the void boundary. In phase field models, the existence of a boundary is indicated by a change in an order parameter. Quantities that are defined along the surface of the boundary are smeared over a narrow region surrounding the boundary. The main advantage of using a phase field model is the ability to retain a fixed finite element mesh for the simulations even as the geometrical
The rate of change of the surface free energy is given by

\[ \dot{W}_{s} = \int_{\Gamma} \gamma d\Gamma \]

where \( \gamma \) is the interfacial tension. The rate of change of the surface free energy can be written as

\[ \dot{W}_{s} = \dot{\gamma} \int_{\Gamma} d\Gamma \]

The surface free energy measures the energetic cost of adding or removing material from the surface of the void. The role played by surface energy in solids is slightly different from that in liquids. In liquids, the surface energy affects both the stress equilibrium of the material and the cost of adding and removing the material. However, in solids the surface energy does not play a significant role in the determination of the deformation equilibrium. The inclusion of a surface term in the expression for the energy makes it possible to model scale effects.

The free energy rate due to electrical work can be approximated in electromigration-induced void evolution problems as

\[ \dot{W}_{e} = \int_{\Omega} \frac{\partial (\rho, \phi_e)}{\partial t} d\Omega + \int_{\Gamma_{int}} (\rho, \phi_e) v_{nd} d\Gamma + \int_{\Gamma_{ext}} \left[ (\rho, \phi_e) v_{nd} \right] d\Gamma \]

where \( \Gamma_{int} \) and \( \Gamma_{ext} \) are the inner and outer boundaries of the system, respectively. The net electrical potential energy is given by

\[ \frac{1}{2} \int_{\Omega} \rho_{e} \phi_{e} d\Omega \]

The rate of change of this quantity, assuming equilibrium is reached for electrical potential much faster than the rest of the system, is obtained by taking the material time derivative of Eq. (4).

\[ \dot{W}_{e} = \int_{\Omega} \frac{\partial (\rho, \phi_e)}{\partial t} d\Omega + \int_{\Gamma_{int}} (\rho, \phi_e) v_{nd} d\Gamma + \int_{\Gamma_{ext}} \left[ (\rho, \phi_e) v_{nd} \right] d\Gamma \]

where \( \Gamma_{ext} \) is the outer boundary of the system.

Minimization of Free Energy Rate. Considering the system shown in Fig. 2, the evolution of a near-equilibrium system can be described by the minimization of the dissipation or of a free energy rate. The free energy rate \( \dot{W} \) in the void evolution problem is written as

\[ \dot{W} = \dot{\Psi} = \dot{\Psi}_s + \dot{\Psi}_e + \dot{\Psi}_m \]

where \( \dot{\Psi} \) is the rate of change of the free energy rate, \( \dot{\Psi}_s \) is the rate of change of the surface free energy, \( \dot{\Psi}_e \) is the rate of change of the electrical potential energy, and \( \dot{\Psi}_m \) is the rate of change of the mechanical energy.

In the above rate, the free energy of the void surface, \( \dot{\Psi}_s \), can be written as

\[ \dot{\Psi}_s = \gamma \int_{\Gamma} d\Gamma \]

Thus, the rate of change of the surface free energy is given by

\[ \dot{\Psi}_s = \gamma v_{nd} \int_{\Gamma} d\Gamma \]

Similarly, the contribution to free energy from mechanical loads is

\[ \dot{\Psi}_m = \int_{\Omega} \phi_m d\Omega \]

where \( \phi_m \) is the strain energy density. To evaluate the mechanical energy contributions, from the balance of mechanical energy on the system, we get

\[ \dot{\Psi}_m = \int_{\Omega} \phi_m d\Omega \]
\[
\int_{\Gamma} \mathbf{r} \cdot \nu d\Gamma = \int_{\Omega} \sigma : D d\Omega \quad (8)
\]

where \( D \) is the rate of deformation tensor. Assuming linear elasticity \( (\sigma = E : \varepsilon) \), and therefore the strain energy density \( \phi_m = \frac{1}{2} E : \varepsilon \), we have, after similar considerations for equilibrium of the stresses

\[
\int_{\Gamma} \mathbf{r} \cdot \nu d\Gamma = \int_{\Omega} \frac{\partial \phi_m}{\partial \nu} d\Omega + \int_{\Gamma_m} \phi_m \nu d\Gamma + \int_{\Gamma_m} \left[ \phi_m \nu_n \right] d\Gamma \quad (9)
\]

Arguing, as before, that the system reaches equilibrium instantly relative to the times involved in mass transport, we have \( \frac{\partial \phi_m}{\partial \nu} \to 0 \). Assuming fixed external boundaries, and no loads in the void, we get

\[
\Psi_m = \int_{\Gamma} \mathbf{r} \cdot \nu d\Gamma = \int_{\Gamma_m} \phi_m \nu d\Gamma \quad (10)
\]

Combining Eqs. (3), (6), and (10), we get

\[
\Psi = \int_{\Gamma_m} [\gamma \kappa + \rho_f \phi_e + \phi_m] \nu d\Gamma \quad (11)
\]

Following the arguments from Ref. [12], and introducing surface and bulk mobilities \( M_s \) and \( M_b \), we get the following equations for the velocity of the front.

For surface diffusion, assuming a local conservation of mass

\[
v_n = \nabla \Gamma \cdot M_s \nabla \Gamma \phi
\]

\[
\phi = \gamma \kappa + \rho_f \phi_e + \phi_m
\]

For the bulk diffusion, we assume that the mass is transferred only from one void surface to another. This leads to an inherently nonlocal equation for the bulk diffusion equations. The equation for the velocity of the void surface is given as

\[
v_n = -M_b[\phi + \lambda]
\]

where \( \lambda \) is a Lagrange multiplier that enforces conservation of mass throughout the system. This constraint can be written as

\[
\int_{\Gamma} v_n d\Gamma = 0 \quad (15)
\]

Finally, the motion under coupled surface and bulk diffusion effects is thus described by

\[
v_n = \nabla \Gamma \cdot M_s \nabla \Gamma \phi - M_b[\phi + \lambda]
\]

This is similar to the Eq. (1.14) derived in Ref. [13]. In Ref. [13], the authors derive the equations using the principles of rational thermodynamics. While the first term in the two equations is the same, the interpretation of the second term differs. While the authors in Ref. [13] use the second and third terms as modeling evaporation and condensation effects from and to the surface, here, on the other hand, we use the terms to mean any rapid transport of material through the bulk of the material.

Diffuse Interface Equations. The equations derived above give us the evolution equations, based on a sharp interface description of the void interface. These have the problem of being difficult to handle when the shape of voids evolve or when there are changes in the topology of the voids since these would require remeshing of the domain. A related challenge is on utilizing the calculated void motion defined on the sharp boundary in a commercial finite element analysis software used to analyze the electrical/mechanical behavior of the system. A diffuse interface approximation for the void interface functions by smoothing the surface over a notional thickness of order \( \epsilon \) and indicating the surface through the level sets of a phase field variable \( u \) that varies from \(-1\) inside the void to \(+1\) outside the void (see Fig. 3). The surface energy (Eq. (2)) is written as

\[
\Psi_s = \frac{1}{c_F} \int_{\Omega} \sqrt{\frac{1}{2} \nabla u^2 + f(u)} \frac{d\Omega}{\epsilon}
\]

where \( c_F \) is a constant scaling parameter defined as in Ref. [14]. The gradient energy was first used in Ref. [15] to study spinodal decomposition in alloys. It was later extended to study other problems with moving boundaries in a diffuse sense, such as solidification [16]. The gradient energy allows the treatment of surface quantities in a diffuse volumetric sense. Locations with nonzero gradients indicate the presence of the interface. The normal to the interface can be inferred by \( \nabla u / \| \nabla u \| \). The term \( f(u) \) in Eq. (17) is a bulk free energy term, with two minima that correspond to the two phases, in this case, the material and the void. The presence of \( f(u) / \epsilon \) in the energy functional penalizes solutions that are not \( \pm 1 \).

A good choice for the potential function is the biquadratic function \( f(u) = \frac{1}{2} \epsilon^2 u^2 \) shown in Fig. 4, \( c_F = \frac{1}{\epsilon} \) and the notional thickness of the interface is \( \epsilon \). Using this description, the equations for the motion of the void can be written in terms of partial differential equations in \( u \). We have, for the surface diffusion problem

\[
\frac{\partial u}{\partial t} = \nabla M_s(u) \nabla \phi
\]

\[
\phi = \frac{1}{c_F \epsilon} \left[ -\gamma (\epsilon^2 \nabla^2 u + f'(u)) + \rho_f \phi_e + \phi_m \right]
\]

where \( M_s(u) \) is restricted to the interfacial region where \(-1 \leq u \leq 1 \). The equation for diffusion through the bulk is given by

\[
\frac{\partial u}{\partial t} = -\frac{M_b}{c_F \epsilon} \left[ \gamma (\epsilon^2 \nabla^2 u + f'(u)) + \rho_f \phi_e + \phi_m + \lambda \right]
\]

\[
\int_{\Gamma} u(t)d\Omega = \int_{\Gamma} u(0)d\Omega
\]

The combined motion of the void surface due to both the surface and the bulk effects is obtained by adding Eqs. (18) and (20). Equation (18) is a specialized version of the Cahn–Hilliard equation [15], while Eq. (20) is a version of the Allen–Cahn equation with an additional constraint on the phase field variable [17].

Numerical Solution

The equations for the void motion are solved in a two-step fashion solving first for the surface diffusion and then solving for the diffusion through the bulk. The partial differential equation for the surface diffusion is 4th order in space. Usually, these equations require \( C^1 \) continuity across element boundaries when using finite element analysis. However, by splitting the governing equations into two 2nd order equations, we can solve these equations using \( C^0 \) elements following the approach outlined in Ref. [18]. As there are no external fluxes, we can assume Neumann boundary conditions everywhere on the boundary.
In order to make the solution procedure robust, we scaled the length by the dimension of the solder joint, $r$, and the time by an arbitrary scale, $\frac{d_{\text{ui}}}{t}$. Further, we scaled the electric potential by the applied potential, and the strain energy with the maximum strain energy observed in the structure. On scaling, Eqs. (18)–(21) become

$$\frac{\partial u}{\partial t} = \nabla^2 \phi$$  \hspace{1cm} (22)

$$\phi = \frac{1}{c_{\text{FE}}} \left[ -(e^2 \nabla^2 u + f'(u)) + \left( k_e \frac{\phi_e}{\phi_w} + k_m \frac{\phi_m}{\phi_w} \right) \right]$$  \hspace{1cm} (23)

$$\frac{\partial u}{\partial t} = \frac{k_d}{c_{\text{FE}}} \left[ (e^2 \nabla^2 u + f'(u)) + r^2 (k_e \frac{\phi_e}{\phi_w} + k_m \frac{\phi_m}{\phi_w} + \lambda) \right] + \int_{\Omega} u(t) d\Omega = \int_{\Omega} u(0) d\Omega$$  \hspace{1cm} (25)

where $k_e = \frac{\phi_e}{\phi_w}$, $k_m = \frac{\phi_m}{\phi_w}$, and $k_d = \frac{M_p}{M_p}$. $k_d$ controls the relative effect of surface diffusion with respect to bulk diffusion. The other parameters control the relative effect of the quantities with respect to the motion due to the reduction of surface energy. Specifically, $k_e$ controls the relative effect between the electric potential and the surface energy, $k_m$ controls the relative effect between the strain energy density and the surface energy, and $k_d$ controls the relative effect of bulk and surface diffusion velocities.

**Discretized Forms of Governing Equations.** Multiplying the equations for surface diffusion (Eq. (18)) by a test function $w$ and integrating by parts, we get

$$\int_{\Omega} w \frac{\partial u}{\partial t} d\Omega = \int_{\Omega} [-M(u) \nabla w \nabla \phi] d\Omega$$  \hspace{1cm} (26)

$$\int_{\Omega} w \phi d\Omega = \int_{\Omega} \left[ \gamma (e^2 \nabla w \nabla u - w f'(u)) + w \rho_e \phi_e + w \phi_m \right] d\Omega$$  \hspace{1cm} (27)

Discretizing the above equations using $C^0$ continuous linear triangular elements (for convenience, since it assures constant derivatives), and assuming that $\frac{\partial u}{\partial t} = u^{i+1} - u^i$, we get

$$\begin{bmatrix} A & \frac{1}{c_{\text{FE}}} \gamma B \cr \Delta t C & A \end{bmatrix} \begin{bmatrix} \phi \\ u^{i+1} \end{bmatrix} = \begin{bmatrix} \frac{1}{c_{\text{FE}}} A (\rho_e \phi_e + \phi_m + \nu f'(u)) \\ \frac{1}{c_{\text{FE}}} A u^i \end{bmatrix}$$  \hspace{1cm} (28)

Here, $A$ is the lumped mass matrix for the system, $B = \int_{\Omega} \nabla N \nabla d\Omega$ and $C = \int_{\Omega} \nabla N_m N d\Omega$. Similarly, for the bulk diffusion equations, by multiplying Eq. (20) by the same test function $w$, we get

$$\int_{\Omega} w \frac{\partial u}{\partial t} d\Omega = \frac{M_p}{c_{\text{FE}}} \int_{\Omega} [-\gamma (e^2 \nabla w \cdot \nabla u + w f'(u)) + w \rho_e \phi_e + w \phi_m] d\Omega + \lambda \int_{\Omega} w d\Omega$$  \hspace{1cm} (29)

$$\int_{\Omega} u d\Omega = \int_{\Omega} u_0 d\Omega$$  \hspace{1cm} (30)

Again, discretizing using $C^0$ linear triangular elements and using an Euler backward scheme, we get the following matrix equations:

$$\begin{bmatrix} \frac{1}{\Delta t} A + \frac{M_p}{c_{\text{FE}}} \gamma e B & a \\ a^T & 0 \end{bmatrix} \begin{bmatrix} \phi^{i+1} \\ \lambda \end{bmatrix} = \begin{bmatrix} \frac{M_p}{c_{\text{FE}}} A (\rho_e \phi_e + \phi_m + \nu f'(u^i)) \\ \int_{\Omega} u_0 d\Omega \end{bmatrix}$$  \hspace{1cm} (31)

Here, $a$ are the diagonal terms of the lumped mass matrix $A$.

The coupled effect of bulk and surface diffusions are accounted for by solving the surface diffusion equation first and then solving the bulk diffusion equation. This is equivalent to solving Eq. (28) first and then solving Eq. (31) using the value of $u^i$ from the solution to Eq. (28).

The solutions for the strain energy, electric potential, and temperature values are obtained by solving the corresponding boundary value problems in a commercial finite element code, using $C^0$ finite elements on the same mesh used for the solution of the phase field problem. The void is indicated by modifying the material properties for Young’s modulus $E$ and electrical conductivity $\eta$ as

$$E(u) = E_0 \left( 1 + \frac{u}{h} \right), \quad \eta(u) = \eta_0 \left( 1 + \frac{u}{h} \right)$$  \hspace{1cm} (32)

**Challenges to Numerical Solution.** As the Cahn–Hilliard equation is a fourth order nonlinear equation, time integration is difficult. Simple explicit solutions such as the forward Euler method are precluded as the time step required for numerical stability is $\approx ch^4$, where $h$ is the size of the element and $c$ is an arbitrary constant. Hence, a semi-implicit method is used for time integration. The mobility and the forces are treated explicitly and are computed and held constant from the end of the time step, while the phase field variable itself is treated implicitly and intrepted for. A further restriction on the time-step size is imposed due to the nonconvex nature of $\rho(u)$. This causes the solution to converge uniformly to either +1 or −1 for large values of time steps. In our studies, we found that the numerical time steps necessary for the convergence of the non-linear solver were on the order of $10^{-4}$ to $10^{-5}$. As this problem is solely due to the numerical difficulties presented by the Cahn–Hilliard equation, the stress and electrical field solution was not recomputed at every time step, but only computed once every few steps of the solution of the diffusion equations. This was also beneficial in reducing the number of times that the commercial solver needed to be called for computing the electrical and stress fields.

**Implementation.** The boundary value problem to obtain the electric field values was solved using a commercial finite element code, using thermoelectric elements. Similarly, the stress problem was solved using plane stress elements. The finite element analysis relied on linear triangular elements. This was linked to the solver for the phase field equations that was written in PYTHON language using SCIPY and SCIPY [19] for the numerical data structures and solvers, respectively. The linear systems were solved using...
the UMFPACK sparse direct solvers. The code developed, *pyPhase*, consists of approximately 1200 lines of *Python* code. The *Python* code includes capabilities to read in information from commercial finite element tools and creating and running simulations. It has the capability of handling arbitrary geometries of solder joints and also assemblies that include multiple joints. The code is independent of the choice of commercial finite element software. The structure of the code is described in Fig. 5.

**Validation**

To validate the model and its implementation, it was tested on rectangular line geometries. In a line that is under the influence of surface diffusion, circular voids would collapse to slits under axial loading, while under electrical loading, the void would move toward the cathode. This is shown in Figs. 6 and 7.

We also tested the solution of the coupled solution including both bulk and surface diffusion. In the absence of any external loading such as electric potential gradients or stress, the system is expected to evolve purely by reduction of the surface free energy. While under surface diffusion, multiple noncircular voids are expected to relax to separate circular voids, with bulk diffusion allowed, smaller voids are expected to lose volume and eventually disappear. This can be tested by varying the relative rate of surface and bulk diffusion.

In Fig. 8, the relative rate of surface and bulk diffusion $k_d$ is varied from 0.1 to 10 from left to right, as can be seen; at high values of $k_d$, the bulk diffusion effect dominates and the smaller void disappears. On the other hand, when the value of $k_d$ is lowered, the area of individual voids is conserved and there is only a relaxation due to the surface diffusion equation.
The 2D model (Fig. 9) was constructed in a commercial finite element tool, according to dimensions from Refs. [20,21]. The material properties used were those of tin (Table 1). The chip side and board side pads were assumed to be made of copper. We assumed that the chip side was at ground, while the board side was maintained at 5 V. The solder joint itself was assumed to be under isothermal conditions. A spatially varying shear displacement was applied on the chip side to simulate the effect of the thermal expansion mismatch. This displacement varied from a value of 0% to 10% of the pad diameter across the diameter of the joint. The interface between the solder joint and the pads was treated as diffusion barrier. This prevents the void from propagating into the pads.

Results and Discussion

Given below are the results of the simulations on the flip-chip solder joint. The problem was scaled and nondimensionalized for numerical stability as described in Eqs. (22)–(25). Specifically, we chose \( r \), the characteristic length, to be the midsection diameter.

![Fig. 9](image-link) Schematic diagram of the solder joint over which the diffusion problem is solved

![Table 1](image-link) Material properties used in the simulations

<table>
<thead>
<tr>
<th>Properties</th>
<th>Cu</th>
<th>Solder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus ( E ) in GPa</td>
<td>128</td>
<td>40</td>
</tr>
<tr>
<td>Poisson’s ratio ( \nu )</td>
<td>0.3</td>
<td>0.36</td>
</tr>
<tr>
<td>Electrical conductivity ( \eta ) in ( \Omega^{-1} \text{ m}^{-1} )</td>
<td>( 6 \times 10^6 )</td>
<td>( 8.7 \times 10^6 )</td>
</tr>
</tbody>
</table>

Flip-Chip Solder Joint Model

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![Fig. 10](image-link) Example showing surface diffusion due to strain energy alone. Here, \( k_d = 0 \), \( k_e = 0 \), and \( k_m = 40 \).

![Fig. 11](image-link) Example showing surface diffusion due to electric potential gradients alone. Here, \( k_d = 0 \), \( k_e = 40 \), and \( k_m = 0 \), as time progresses the void rearranges into a pancake formation, similar to that shown in Fig. 1.

![Fig. 12](image-link) Example showing significant diffusion through the bulk of the material. Here, \( k_d = 5 \), \( k_e = 20 \), and \( k_m = 20 \).

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ter of the solder joint. As described earlier, we also used a normalized timescale $\tau = \frac{s}{c}r$.

**Surface Diffusion.** We first demonstrate our model on examples that are limited solely to surface diffusion. In this case, Eq. (20) is deactivated and not solved. The first example illustrates the effect of strain energy alone on the void motion (Fig. 10). In the next example, we simulate the motion of a void surface due to the electrical effects alone (Fig. 11). We see that in these cases the strain energy density and electrical effects cause the void to evolve in opposite directions. The evolution under an electrical field leads quite quickly to a pancake shaped void that has the potential to cause electrical failure. This is due to the fact that the electric current pushes the particles away from the current crowding region. Hence, it is expected that the voids in the solder migrate to this location. For the case with strain energy driven diffusion, the reason for the direction of the void surface motion is that even though the mechanical loading is a horizontal shear force. The direction of the strain energy gradient is tangential to the surface of the void. This causes the void to tend to collapse in that direction (see Fig. 12).

**Combined Bulk and Surface Diffusion.** In real applications, both surface and bulk diffusions are significant. This leads to a void growth analogous to Ostwald ripening effect observed in heterogeneous microstructures where one void grows at the expense of another. Shown in Fig. 13 is a case where there is a significant diffusion through the bulk. It is observed that the system evolves by transferring the mass to the void closest to the current crowding corner. The farther void reduces in size, until it is completely dissolved. The reason for this location of the final void configuration is the same as the explanation for the position of the void for the case with only surface diffusion.

**Simulating Electromigration in Assemblies of Solder Joints.** The electromigration in real solder joints is subject to effects that are visible only in assemblies of solder joints. One of these is the effect of the direction of the current in the current crowding region on the propagation of voids. In this example, an assembly of two solder joints is considered. The dimensions and loading of this assembly are described in Fig. 14. The entire joint is loaded by applying a potential difference of 10 V across the two solder joints. Additionally, a shear force is simulated on the two solder joints by applying a deformation of 10% of the midsolder section diameter on the joints (13.2 μm) in each of the joints. By loading the assembly in this fashion, one is able to consider the effect of the direction of the current in the current crowding region on the motion of the voids since, for instance, the top left corner of the first joint and the top right corner of the second joint experience opposite current directions, while maintaining the mechanical load direction to be the same.

In the first case (Fig. 15), the effects of the strain energy driven diffusion are turned off by setting $k_m = 0$. The direction of the current in the left solder joint causes the void to move into the current crowding region and form a pancake like void in that region, while in the right joint, the direction of the current is reversed and the void is pushed into the solder joint. Figure 16 illustrates the effect of mechanical load alone on the evolution of the void, and provides the baseline for the study of the effect of strain energy distribution on the electromigration of the void. As before, to understand the reason for the evolution of the void into the bulk of the solder joint, it is illustrative to study the strain energy distribution in the solder joint (Fig. 17). In Fig. 18, the combined effects of both electromigration and stress-induced void evolution are illustrated. As can be seen, the strain energy gradient causes the void to evolve in a direction counter to the direction of the electromigration. In this case, it slows down the evolution of the void toward the current crowding region. This suggests that the severity
of failure due to the electromigration of voids might depend significantly on the position of the solder joint in the package, depending on the type and severity of the mechanical loading seen by each joint.

Summary

We demonstrated, in this work, a phase field method to simulate the motion of pre-existing voids in the flip-chip solder joints. We detailed the sharp interface equations for the motion of a void in a material evolving under the influence of surface energy, strain energy, and electric potential. This is related to diffuse interface equations that reduce in the limit of ε to the sharp interface equations, and tracks the motion of the interface. The equations presented here account for the surface diffusion and also the bulk diffusion between multiple voids. The numerical solution to these equations is implemented into a numerical framework that uses a commercial finite element code to solve for the stress and electrical potential fields. We use this system to study the dynamics of void motion in a two-dimensional model of a flip-chip solder joint assembly. We showed the effects of introducing a void in the current crowding region of the solder interconnect. It was found that the electromigration void evolution depends on the directionality of current, with a pancake void forming in the cathodic region and the void migrating into the interior of the joint away from the interface near the anodic region. Further, the stress-induced void migration direction is opposite to that of current-induced void migration, and as a result, failure is likely to depend on the local configuration of the solder joint in the array, the presence of significant shear loading, and the direction of current. Electromigration in solders is a highly complicated process and while the model shown here gives us an indication to the likely direction of the motion of the void, the role of plasticity, and the initiation of voids needs to be accounted for in the models in a thermodynamically consistent way. This is currently under investigation.

Acknowledgment

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Nomenclature

- \( v_n \): normal velocity at a point on the boundary of the void
- \( u, f(t) \): phase field order parameter, phase field potential function
- \( c_p \): velocity scaling parameter
- \( \Psi \): free energy
- \( \tau \): surface energy density
- \( E \): Young’s modulus
- \( \eta \): electrical conductivity
- \( \phi_e, \phi_0 \): electric potential in domain, applied electric potential
- \( \phi_m, \phi_{b0} \): strain energy density in domain, maximum strain energy density
- \( k_e \): mean curvature
- \( c \): notional interface thickness
- \( \rho_e \): charge density
- \( M_s \): surface diffusion mobility
- \( M_b \): bulk diffusion mobility
- \( k_s \): scaling parameter accounting for the relative magnitudes of bulk and surface mobility
- \( \beta \): Lagrange multiplier for global conservation of mass
- \( \kappa \): scaled time

References


