Moisture Diffusion and Integrated Stress Analysis in Encapsulated Microelectronics Devices

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Abstract
In this paper, a damage mechanics-based continuum theory is developed to provide a theoretical framework for multi-field problems involving moisture diffusion, heat conduction, moisture evaporation, void growth, and material deformation in a temperature and time-dependent process in encapsulated microelectronics devices. The analysis of moisture diffusion using normalized moisture concentration is re-examined under various conditions, and the applicability of the thermal-moisture analogy is discussed. Effective stress concept is introduced to consider the effect of vapor pressure in the development of a continuum mechanics framework. It turns out that the volumetric strains consist of three parts: thermal expansion (or contraction), hygroscopic swelling, and vapor pressure-induced volumetric strains. Void volume fraction is introduced as a field variable to describe the damage progression. The evolution of void volume fraction is governed by the continuity equation. Vapor pressure considered as another internal field variable, which is related to moisture evaporation. A complete set of multi-field governing equations are developed. A simplified process, which allows the coupled problem to be solved sequentially, is defined. A bi-material assembly is used to illustrate the multi-field solutions using ANSYS.

1. Introduction
Extensive studies have been made to investigate the moisture diffusion, desorption, and ensuing mechanical stresses in encapsulated microelectronics devices (Liu et al., 1995; Tay et al., 1996, 1999; Galloway et al., 1997; Fan et al., 1999). Specific interests have been focused on the reflow process, in which temperature ramps up in approximately 3 to 5 minutes to a peak temperature of 260°C at the rate of 0.5 to 2.0°C per second (Kitano et al., 1988; Tee et al., 2004; Fan et al., 2008a; Fan and Suhir, 2010). The encapsulated moisture, which was absorbed at preconditioning phase, when temperature and relative humidity remain constants throughout moisture absorption. During reflow process, however, thermal-moisture analogy is not valid anymore due to the temperature-dependence of material’s solubility (Xie et al., 2009 (a), (b)).

Thermal mismatch, hygroscopic swelling, and internal vapor pressure are applied simultaneously to the encapsulated microelectronic devices at reflow. The equivalent coefficient of thermal expansion (CTE) method is used for an integrated stress analysis to consider the combined effects of thermal expansion, hygroscopic swelling, and vapor pressure-induced strains (Tee et al., 2004). In the equivalent CTE method, a saturated and uniform moisture distribution is assumed for an entire reflow process. However, time-dependent and non-uniform moisture distribution process is not taken into considerations. In addition, the equivalent CTE method cannot be extended to non-linear and time-dependent analysis since it is based on a linear superposition (Fan et al., 2008b).

This paper starts with the examination of mass diffusion equation with varying temperature and relative humidity (RH) conditions. Then a self-consistent framework of damage mechanics-based continuum theory is developed. The concept of effective stress is introduced using micromechanics analysis. Void volume fraction and vapor pressure are introduced as two internal field variables. A complete set of governing equations including temperature, moisture, displacement, void volume fraction, and vapor pressure is established. This paper also presents a simplified process for multi-field problems. Commercial finite element analysis software ANSYS is used to solve the problems. A representative bi-material configuration is used to illustrate the solutions for moisture diffusion, vapor pressure, and integrated stress analysis.

2. Moisture Diffusion
Moisture diffusion behavior is often described by Fick’s law (Crank, 1956):

$$ \dot{J} = -D \nabla C $$

(1)

where D is diffusivity for moisture diffusion, $\nabla C$ the moisture concentration gradient and $\dot{J}$ is the flux vector. The general form of diffusion equation is
Where $S$ is the solubility in the base material. When two dissimilar materials are joined at an interface, the normalized concentration $\varphi$ is continuous across the interface between the two different materials. Equation (2) in terms of the normalized concentration $\varphi$ becomes

$$
\nabla \cdot D [\nabla \varphi + \varphi \frac{\partial S}{\partial T} \nabla T] = S \frac{\partial \varphi}{\partial t} + \varphi \frac{\partial S}{\partial T} \frac{\partial T}{\partial t}
$$

(4)
in which the solubility is a function of temperature $T$. The above equation is not truly analogous to the original diffusion equation (2) if

$$
\frac{\partial S}{\partial t} = 0, \quad \nabla T = 0
$$

(5)

On the other hand, a general form of moisture diffusion constitutive model can be written as (Sofronis and McMeeking, 1989)

$$
\vec{J} = -SD[\nabla \varphi + \kappa_1 \nabla T + \kappa_2 \nabla p]
$$

(6)

where $\kappa_1$ and $\kappa_2$ are temperature and pressure gradient factors, providing diffusion driven by the gradient of temperature and pressure stress, respectively. The pressure $p$ is defined as $-\sigma / 3$. The temperature gradient driven term in equation (4) can be recovered by equation (6) with

$$
\kappa_1 = \frac{\varphi \frac{\partial S}{\partial T}}{S \frac{\partial T}{\partial t}}
$$

(7)

Equation (4) indicates that Equation (4) based on the normalized variable can be considered as a special case of a general type of moisture diffusion by Equation (6).

When a constant temperature process with varying humidity condition is considered, the solubility $S$ is a constant. Equation (4) is reduced to the original Fick diffusion

$$
\nabla \cdot D [\nabla \varphi] = \frac{\partial \varphi}{\partial t}
$$

(8)

which means that the so-called thermal-moisture analogy can be applied to the moisture absorption process with varying humidity conditions but maintaining a constant temperature.

Wong et al. (1998) proposed an alternative normalized variable, called wetness $w$, by

$$
w = \frac{C}{C_{sat}}
$$

(9)

where $C_{sat}$ is taken as the saturated moisture concentration at a given relative humidity condition and a given temperature state. Since $C_{sat}$ is not exactly a material property due to its dependence on the relative humidity, it is ambiguous to extend the above approach to a varying humidity condition, such as in a process from soaking to reflow, where relative humidity changes. Jang et al. (2008) recognized that the saturated moisture concentration depends linearly on the relative humidity, and is independent of temperature. They introduced an advanced analogy methodology based on a ‘constant’ saturated moisture concentration $M$. To be clearer, we introduce a normalized variable, without losing generality, symbol $w$ is still used, as follows

$$
w = \frac{C}{C_{sat}(RH_0, T)}
$$

(10)

where $RH_0$ is the relative humidity at a reference humidity condition. Equation (10) now has an unambiguous definition with respect to what ‘$C_{sat}$’ is used in Equation (9). For a varying relative humidity process, the denominator in equation (10) always refers to a ‘reference’ saturated moisture concentration at $RH_0$ and $T$, even though $RH_0$ may be different from the current relative humidity conditions. With Henry’s law (Crank, 1956)

$$
C_{sat}(T, RH_0) = p_{amb}(RH_0, T)S(T)
$$

(11)

where

$$
p_{amb}(RH_0, T) = RH_0 \cdot p_g(T)
$$

(12)

where $p_{amb}$ and $p_g$ are partial pressure at $RH_0$ and saturated vapor pressure of moisture at temperature $T$. It can be seen that $w$ is continuous at the interface of dissimilar materials.

It has been observed that the saturated concentration is linearly proportional to the ambient relative humidity but not dependent on the temperature, as long as it is far away from the glass transition temperature (He et al., 2007; Fan et al., 2009; Fan and Suhir, 2010). In this case, the $C_{sat}(RH_0, T)$ can be considered as a constant within the interested temperature range. Substituting Equation (10) into Equations (2) and (1), we obtain

$$
\nabla \cdot D \nabla w = \frac{\partial w}{\partial t}
$$

(13)

which indicates that the thermal-moisture analogy holds true for a temperature-dependent moisture diffusion process when $w$ in Equation (10) is used.

It is noted that when Equation (10) is used, the boundary condition becomes

$$
w = \frac{C_{sat}(RH, T)}{C_{sat}(RH_0, T)} = \frac{RH}{RH_0}
$$

(14)

Therefore, $w=1$ if $RH=RH_0$ (preconditioning), and $w=0$ if $RH=0$ (desorption at reflow).

3. Effective Stress and Continuum Theory

Polymeric materials can be considered as porous media. When moisture is vaporized, all-round vapor pressure generated by moisture evaporation is exerted on the solid phase of the material. To describe the coupling phenomena between vapor pressure and matrix material deformation, the effective stress concept is introduced.
using a micromechanics analysis (Terzaghi, 1943)

$$\sigma_y = \sigma_y' - p\delta_y$$  \hspace{1cm} (15)

where $\sigma_y$ is the total stress tensor component, and $p$, the vapor pressure, and $\sigma_y'$ is the effective stress. Please note the vapor pressure $p$ in equation (15) has a different meaning of the pressure stress used in previous section for a general type of diffusion constitutive model. In equation (15), $p$ is the vapor pressure due to moisture and has a positive value. According to the definition of effective stress, the deformation of porous skeleton is governed by the effective stress only. For example, if a linear, isotropic elastic material is considered, the constitutive model can be described by the effective stress as follows,

$$\varepsilon_y = \frac{1}{E} \sigma_y - \frac{\nu}{E\sigma_y} \sigma_{ik} \delta_{y} + (\alpha \Delta T + \beta C) \delta_y$$  \hspace{1cm} (16)

where $E$ and $\nu$ are Young’s modulus, and Poisson’s ratio, respectively, and $\alpha$, $\beta$ are the coefficients of thermal expansion, and hygroscopic swelling, respectively. $\Delta T = T - T_0$, $T_0$ is a reference temperature, and $C$ is the moisture concentration. By substituting Equation (16) into Equation (15), one obtains

$$\varepsilon_y = \frac{1}{E} \sigma_y - \frac{\nu}{E\sigma_y} \sigma_{ik} \delta_{y} + (\alpha \Delta T + \beta C + \frac{1-2\nu}{E} p) \delta_y$$  \hspace{1cm} (17)

Equation (17) indicates that the vapor pressure contributes to the matrix deformation as an additional volumetric strain term. The total volumetric strain becomes

$$\varepsilon_{y \text{vol}} = \alpha \Delta T + \beta C + \frac{1-2\nu}{E} p$$  \hspace{1cm} (18)

Equation (18) can be also written as

$$\sigma_y = 2G\varepsilon_y + \lambda\varepsilon_{ik} \delta_{y} - \frac{E}{1-2\nu} (\alpha \Delta T + \beta C + p) \delta_y$$  \hspace{1cm} (19)

where $G$ and $\lambda$ are Lame’s elastic constants. The deformation equilibrium now becomes

$$GV^2 u_i + (\lambda + G) e_{ij} [\frac{E}{1-2\nu} (\alpha \Delta T + \beta C + p)]_{ij} + X_i = 0$$  \hspace{1cm} (20)

where $u_i$ is the component of displacement vector, $e$ is the total volumetric strain $e^{\text{vol}}$, $X_i$ is the component of body force vector. Equation (18) or Equation (20) implies that all applied loads: thermal expansion, hygroscopic swelling and vapor pressure, are in the forms of body loads. The resulting stress/deformation response caused by temperature excursion and moisture diffusion and evaporation can be obtained by solving the force equilibrium equation with the above strain definitions and the governing equations of heat conduction and moisture diffusion. Since they are virtually independent of the stress state (if stress gradient-driven diffusion mechanism can be neglected), the temperature and moisture concentration fields can be determined, respectively, prior to a stress analysis, and then they can be incorporated into a subsequent stress analysis. However, vapor pressure in equation (20) must be determined before the stress analysis. Vapor pressure is related to the local moisture concentration and free volume fraction growth, which is coupled with the matrix’s deformation. The equations of vapor pressure model and void volume fraction growth are described in the next section.

4. Vapor Pressure Model and Free Volume Fraction Evolution

Although moisture diffusion is analyzed at a macroscopic level, the vapor pressure model should be considered at a microscopic level (Fan et al., 2005). Moisture exists everywhere in polymer materials, and stays either in the mixed liquid/vapor phase or in the single vapor phase in nano-pores or in free volumes, as shown in Figure 1. Assume that all moisture absorbed is in free (‘unbound’) water liquid or vapor form. Moisture collects at the micro-/nano- pores, in free volumes, at the interfaces, and/or in micro/macro-voids (Fan et al., 2009). Unbound moisture will evaporate during the refloex process.

![Figure 1 'Porous' polymer material and moisture inside free volumes or voids](image)

A representative elementary volume (REV) around any considered point in porous medium is considered. The REV is defined in such a way that wherever it is placed within the considered porous medium domain, it always contains both the solid polymer phase and the porous/free volume phase. The total moisture content in a REV is obtained from the local moisture concentration $C$ at a macroscopic level. If the void volume fraction $f$ (or interstitial space fraction) is known, then the ‘apparent’ moisture density ($\rho$) in pores can be defined as (Fan et al., 2005)

$$\rho = C / f$$  \hspace{1cm} (21)

When the moisture density $\rho$ in pores is less than the saturated water vapor density $\rho_w$, the moisture is in the single vapor phase. In this case, since the total moisture content ($C^*V$, where $V$ is REV volume), and the free volume ($f^*V$) are known, the vapor pressure can be obtained using the ideal gas law as follows

$$p(T) = \frac{RT}{MM_{H,O} f} \cdot C$$  \hspace{1cm} when $C(T)/f < \rho_w(T)$  \hspace{1cm} (22)

here $R$ is the universal gas constant ($=8.314/(\text{mol} \cdot \text{K})$), and $MM_{H,O}$ is the molecular mass of water ($=18g/mol$). On the other hands, when the moisture density $\rho$ is equal to or greater than the saturated water vapor density $\rho_w$, the moisture in pores is in the mixed liquid-vapor phase. Therefore the vapor pressure remains as the saturated vapor pressure, as follows


\[ p(T) = p_a(T), \quad \text{when} \quad C(T)/f \geq \rho_a(T) \]  

(23)

where \( p_a \) is the saturated water vapor pressure. Equations (22) and (23) provide the models to calculate vapor pressure. It indicates that vapor pressure is related to moisture diffusion (moisture concentration \( C \)), and temperature field \( T \), as well as the growth of the void volume fraction \( f \). The void volume fraction may be considered as a damage field variable. The growth of the void must follow the continuity equation, as follows (Fung, 1965),

\[ f = (1 - f)\dot{u}_{ij} \]  

(24)

which is coupled with the continuum’s deformation in equation (20).

5. Summary of Governing Equations

From the analysis in the previous sections, the basic field variables of the problem include: temperature \( T \), normalized moisture concentration \( \phi \), displacement vector \( \dot{u}_{ij} \), internal vapor pressure \( p \), and void volume fraction \( f \). The vapor pressure \( p \) and void volume fraction \( f \) can be considered as internal field variables. Void volume fraction \( f \) is a damage parameter to describe the progression of damage in a system of interest. The governing equations for solving the problem are summarized as follows

\[ \nabla \cdot k(\nabla T) = c_r \rho \frac{\partial T}{\partial t} \]  

(25a)

\[ \nabla \cdot D(\nabla \phi + \phi \frac{\partial S}{\partial T} \nabla T) = S \frac{\partial \phi}{\partial t} + \phi \frac{\partial S}{\partial T} \frac{\partial T}{\partial t} \]  

(25b)

\[ C = \phi S \]  

(25c)

\[ GV^2 \dot{u}_i + (\lambda + G) \varepsilon_{ii} \left[ -\frac{E}{1-2\nu} (\alpha \Delta T + \beta C) + p \right]_{ij} + X_i = 0 \]  

(25d)

\[ p = \frac{RT}{MM_n \phi_f} \rho_a \]  

(25e)

\[ C / f \geq \rho_a(T) \]  

(25f)

\[ f = (1 - f)\dot{u}_{ij} \]  

(25g)

It is noted that the above equations are based on a linear elastic and small deformation analysis. The framework can be extended to nonlinear analysis involving material nonlinear behavior, such as viscoelastic or viscoplastic, plastic deformation, and also geometrical nonlinear behavior, i.e., large deformation.

6. A Simplified Approximation

Solving multi-field equations simultaneously is too complicated to be practiced in most engineering applications. In this section we introduce a simplified process so that the multi-field problems become sequentially coupled problems. We consider a typical process that starts from moisture soaking and finishes with a reflow process. Such a process involves both moisture soaking and desorption stages. Since heat conduction in microelectronic devices is several orders of magnitudes faster than moisture diffusion, isothermal condition is assumed throughout the process. The addition of heat conduction can be implemented numerically without any difficulty, but for clarity purpose, isothermal condition is assumed here. Next, Fickian moisture diffusion is considered. The saturated moisture concentration of each material at a given relative humidity condition is assumed as a constant throughout the process. Such an assumption is not true for most of polymer materials in a typical reflow temperature range. The saturated moisture concentration changes dramatically when the temperature ramps across the glass transition temperature during reflow. Since our interests focus on the subsequent integrated stress analysis, we keep this assumption so that the moisture diffusion from moisture soaking to reflow can be solved with a thermal-moisture analogy (using Equation (10)). Furthermore, we assume that voids do not grow significantly so that the vapor pressure can be calculated based on the instantaneous local moisture concentration. The integrated stress analysis can then be followed with the combined body loads of thermal expansion, hygroscopic swelling, and vapor pressure-induced expansion. The field equations to be solved now become

\[ \nabla \cdot D \nabla w = \frac{\partial \omega}{\partial t} \]  

(26a)

\[ C = C_{\omega \phi} (RH_0, T) \cdot w \]  

(26b)

\[ p = \frac{RT}{MM_n \phi_f} \rho_a \]  

(26c)

\[ GV^2 \dot{u}_i + \lambda \varepsilon_{ii} \left[ -\frac{E}{1-2\nu} (\alpha \Delta T + \beta C) + p \right]_{ij} + X_i = 0 \]  

(26d)

in which moisture diffusion can be solved first. Then whole-field vapor pressure distribution can be obtained based on the solution of moisture concentration and the known initial void volume fraction. Finally the structural analysis can be solved with the combined body loads of thermal expansion, hygroscopic swelling, and vapor pressure-induced expansion. In a stress analysis, the volumetric strain at time step \( \tau \) can be calculated by

\[ e^{\text{vol}} = \alpha \Delta T + \beta \left[ C + \left( \frac{1-2\nu}{2} \right) p \right] = \alpha \Delta T + \beta \cdot g(C) \]  

(27)

where \( g(C) \) is a function of moisture concentration including the effects of both hygroscopic swelling and vapor pressure. ANSYS offers two types of body loads; temperature and fluence. The fluence is a source causing isotropic swelling of materials considered. In the default built-in USERSW option, the relationship between a swelling strain \( e^{sw} \) and a fluence is defined as (ANSYS, 2010; Jang et al., 2010)

\[ e^{sw} = r \cdot g^n \]  

(28)

where \( r \) is a swelling rate, \( g \) is a fluence and \( n \) is an exponent. Equation (28) can be used to define the second term of the right side of equation (27) when \( n, r \) and \( g \) are replaced with 1, \( \beta \) and \( g(C) \), respectively. Since the
swelling law of equation (28) is available with a built-in default USERSW, neither modification of the user subroutine nor compile/link process is required for the combined hygro-thermo-mechanical analysis using ANSYS.

7. An Example

A bi-material configuration, which is made of copper and mold compound, is used as an illustration of a sequentially coupled moisture diffusion, vapor pressure, and integrated stress analysis. The geometry and material properties are given in Tables 1 to 3, respectively. Diffusivity for mold compound follows Arrhenius relationship

\[
D = D_0 \exp\left(-\frac{Q}{R_0 T}\right)
\]

where \(D_0\) and \(Q\) are pre-factor and activation energy, respectively, and \(R_0 = 8.3145\) J/molK. Copper does not absorb moisture, therefore the diffusivity and saturated moisture concentration are assigned to very small (e.g. \(10^{-6}\) lower) values.

### Figure 2 Copper/mold compound bi-assembly

Table 1 Bi-material assembly geometry

<table>
<thead>
<tr>
<th></th>
<th>Copper</th>
<th>Mold compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>0.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 2 Material properties of bi-material assembly

<table>
<thead>
<tr>
<th></th>
<th>Copper</th>
<th>Mold compound</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs at 85°C/85%RH ((\mu g/\text{mm}^3))</td>
<td>N/A</td>
<td>4.0</td>
</tr>
<tr>
<td>Diffusivity pre-factor (D_0) (mm(^2)/s)</td>
<td>N/A</td>
<td>5.0</td>
</tr>
<tr>
<td>Diffusivity activation energy (Q) (ev)</td>
<td>N/A</td>
<td>0.4</td>
</tr>
<tr>
<td>Initial void volume fraction</td>
<td>N/A</td>
<td>0.05</td>
</tr>
<tr>
<td>Coefficient of thermal expansion (ppm/°C)</td>
<td>17</td>
<td>see Table 3</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>130</td>
<td>see Table 3</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.34</td>
<td>0.3</td>
</tr>
<tr>
<td>Coefficient of hygroscopic swelling (mm(^3)/(\mu g))</td>
<td>N/A</td>
<td>(0.5\times10^{-3})</td>
</tr>
</tbody>
</table>

Table 3 Temperature-dependent material properties for mold compound

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>CTE (ppm/°C)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>20</td>
<td>20.0</td>
</tr>
<tr>
<td>125</td>
<td>20</td>
<td>20.0</td>
</tr>
<tr>
<td>155</td>
<td>40</td>
<td>5.0</td>
</tr>
<tr>
<td>195</td>
<td>40</td>
<td>1.0</td>
</tr>
<tr>
<td>265</td>
<td>40</td>
<td>1.0</td>
</tr>
</tbody>
</table>

An initial stress-free condition of 160°C for the assembly is assumed when two materials are joined together. Both materials are assumed to be linear elastic. The assembly initially experiences preconditioning at 85°C/85%RH for 196 hours, followed immediately with a reflow process. The time history of the reflow process is depicted by Figure 3. The reflow temperature profile affects moisture distribution greatly.

Figure 4 shows the absolute moisture concentration contour plots at three different temperatures during reflow. It can be seen that the maximum moisture concentration at copper/mold compound interface decreases significantly due to desorption. Figure 5 gives the vapor pressure contour plots at the same three temperatures. Vapor pressure initially increases with temperature from 200°C to 260°C despite that the moisture concentration decreases. However, with more moisture lost during heating, vapor pressure starts to decrease even though when temperature continues to rise. This indicates that there is not sufficient residual moisture to keep the high vapor pressure.
Figure 6 shows the comparison of moisture distributions at 1 hour and 18 hours in preconditioning under 85°C/85%RH, and the corresponding deformed shapes of the assembly and the maximum von Mises stresses in mold compound. In the beginning of preconditioning, the assembly is in convex shape due to thermal mismatch from stress free of 160°C to 85°C. Afterwards mold compound swells with moisture absorption, and the assembly deforms from convex to concave shape. At the same time, stress level in mold compound increases significantly due to hygroscopic swelling.

After the moisture concentration and vapor pressure fields are determined, they can be incorporated into a subsequent stress analysis using equation (27). To make comparisons for the effects of hygroscopic swelling and vapor pressure, three types of stress analysis are conducted,

1. Type 1: thermal load only. In this analysis, only thermal mismatch is considered at the reflow. Since it is a linear analysis, the stress state depends on the final temperature state only.
2. Type 2: combined thermal and hygroscopic swelling loads. At different times in the studied process (either in preconditioning or reflow stage), moisture distributions can be applied as body loads using fluence. The stress state depends on the temperature state and instantaneous moisture distributions.
3. Type 3: combined thermal, hygroscopic swelling and vapor pressure loads. In this case, equation (27) is used to apply a body load of g(C), which comprises both hygroscopic swelling and vapor pressure.

Table 4 shows the maximum warpage, maximum von Mises stresses in copper and mold compound, respectively, at three different times during reflow: 200°C, 260°C, and 200°C after 30 seconds hold. At 200°C, hygroscopic swelling and vapor pressure induced stresses play significant roles in final stress state. Results indicate that the effects of hygroscopic swelling and vapor pressure cannot be overlooked. From Table 5 and Table 6, it is apparent that the effects of hygroscopic swelling and vapor pressure fade when more moisture is lost. The maximum stress state can be determined at a certain temperature with given reflow profile and the maximum stress may not occur at the peak reflow temperature since moisture continues to escape during temperature rise.

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Table 4 Maximum warpage ($w$) and von Mises stresses ($\sigma_e$) in copper and mold compound at 200$^\circ$C

<table>
<thead>
<tr>
<th></th>
<th>$w$ (mm)</th>
<th>$\sigma_e$ MC (MPa)</th>
<th>$\sigma_e$ Cu (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal stress only</td>
<td>0.4e-3</td>
<td>2.4</td>
<td>8.7</td>
</tr>
<tr>
<td>Thermal + hygroscopic</td>
<td>0.7e-3</td>
<td>4.9</td>
<td>17.3</td>
</tr>
<tr>
<td>Thermal + hygroscopic + vapor pressure effect</td>
<td>1.0e-3</td>
<td>6.3</td>
<td>22.9</td>
</tr>
</tbody>
</table>

Table 5 Maximum warpage ($w$) and von Mises stresses ($\sigma_e$) in copper and mold compound at 260$^\circ$C

<table>
<thead>
<tr>
<th></th>
<th>$w$ (mm)</th>
<th>$\sigma_e$ MC (MPa)</th>
<th>$\sigma_e$ Cu (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal stress only</td>
<td>1.3e-3</td>
<td>6.0</td>
<td>21.9</td>
</tr>
<tr>
<td>Thermal + hygroscopic</td>
<td>1.5e-3</td>
<td>7.2</td>
<td>27.5</td>
</tr>
<tr>
<td>Thermal + hygroscopic + vapor pressure effect</td>
<td>2.1e-3</td>
<td>11.2</td>
<td>38.9</td>
</tr>
</tbody>
</table>

Table 6 Maximum warpage ($w$) and von Mises stresses ($\sigma_e$) in copper and mold compound at 260$^\circ$C after 30 seconds hold

<table>
<thead>
<tr>
<th></th>
<th>$w$ (mm)</th>
<th>$\sigma_e$ MC (MPa)</th>
<th>$\sigma_e$ Cu (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal stress only</td>
<td>1.3e-3</td>
<td>6.0</td>
<td>21.9</td>
</tr>
<tr>
<td>Thermal + hygroscopic</td>
<td>1.4e-3</td>
<td>6.3</td>
<td>24.7</td>
</tr>
<tr>
<td>Thermal + hygroscopic + vapor pressure effect</td>
<td>1.4e-3</td>
<td>6.3</td>
<td>24.7</td>
</tr>
</tbody>
</table>

8. Concluding Remarks

This paper presents a self-consistent continuum mechanics theory for multi-field problems in encapsulated microelectronic devices. The effective stress concept is employed to take the moisture vapor pressure into considerations. Vapor pressure model based on a micromechanics analysis provides the relationship between moisture diffusion and void volume growth. A continuum equation is derived for void volume fraction evolution. Both vapor pressure and void volume fraction are newly introduced field variables, which are coupled with moisture diffusion, material deformation and heat conduction. A simplified process is introduced to solve those multi-field equations sequentially using thermal-moisture analogy and built-in user-defined swelling functions in ANSYS. A bi-material assembly is used to illustrate the integrated analysis of moisture diffusion, vapor pressure evolution and stress determinations.

Acknowledgement

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1. ANSYS Manual 11.0. 2010


