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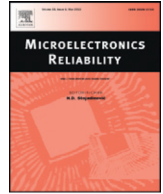

Peridynamic wetness approach for moisture concentration analysis in electronic packages

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ABSTRACT

Within the finite element framework, a commonly accepted indirect approach employs the concept of normalized concentration to compute moisture concentration. It is referred to as "wetness" approach. If the saturated concentration value is not dependent on temperature or time, the wetness equation is analogous to the standard diffusion equation whose solution can be constructed by using any commercial finite element analysis software such as ANSYS. However, the time dependency of saturated concentration requires special treatment under temperature dependent environmental conditions such as reflow process. As a result, the wetness equation is not directly analogous to the standard diffusion equation. This study presents the peridynamic wetness modeling for time dependent saturated concentration for computation of moisture concentration in electronic packages. It is computationally efficient as well as easy to implement without any iterations in each time step. Numerical results concerning the one-dimensional analysis illustrate the accuracy of this approach. Moisture concentration calculation in a three-dimensional electronic package configuration with many different material layers demonstrates its robustness.

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1. Introduction

The components of Integrated Circuit (IC) devices are susceptible to moisture absorption at different stages of the production environment. The differential swelling between the polymeric and nonpolymeric materials, and among the polymeric materials exacerbates the hygrothermal stresses during the surface mounting (solder reflow) process in which the temperature of the IC package increases from room temperature to about 220 °C. Since the temperature at this stage is higher than the glass transition temperature of polymeric materials, their mechanical properties degrade significantly. Thus, coupled with the vapor pressure in micro voids, hygro-mechanical and thermo-mechanical stresses may cause delamination, and subsequent cracking at different interfacial sites within the electronic package. Delamination or cracking is one of the primary failure mechanisms in plastic IC packages and often lowers the threshold for other mechanical, and electrical failures. The hygro-mechanical stresses induced through moisture preconditioning or pre-baking are significant compared to the thermo-mechanical stresses induced during the solder reflow. Combination of these stresses can be detrimental to the reliability of the IC packages.

JEDEC standard (J-STD-020) [1] defines the necessary baking procedures to remove the trapped moisture in order to prevent cracking and delamination failures during the reflow process. The bake-out times were established based on weight gain/loss measurements and one-dimensional diffusion analysis for a homogeneous medium. Such measurements require undesirable long test times (192 or 168 h); however, they can also be used to establish accelerated equivalent conditions for moisture preconditioning.

The moisture absorption/desorption induced failures in IC packages is more crucial for the durability of three-dimensional (3D) electronic packages with through-silicon via (TSV), ultrathin and multi-die stacking technology. However, techniques for in-situ measurement of moisture concentration within electronic packages do not exist due to the small length scales. Furthermore, the comparison of the weight gain of IC packages may not correlate with a moisture concentration inside the IC packages [2–4]. Also, Kitano et al. [2] demonstrated that the package cracking is not controlled by the absolute weight gain of packages, but the local moisture concentration at the critical interface. Therefore, it is of critical concern to compute the extent of moisture content in electronic packages.

Consequently, numerical simulation techniques have become an essential part of electronic packaging design and manufacturing for acceptable reliability. Many commercially available finite element programs are capable of solving the diffusion equation. The field

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variable must be continuous within the domain as a result of the nodal continuity requirement of Finite Element Method (FEM). However, it is worth noting that the saturated concentration of each material is different. Therefore, the direct solution of moisture concentration with FEM using traditional elements is not possible because continuity of concentration is required at the interface nodes. This requirement is satisfied by considering a normalized concentration (wetness) parameter introduced by Wong et al. [5]. The "wetness" parameter is the ratio of moisture concentration to its saturated moisture concentration. It is continuous across material interfaces. In FEM, the wetness analysis is performed through the concept of thermal-wetness analogy. By adjusting the thermal diffusion parameters properly, the thermal diffusion capability of a commercial finite element program can be utilized to solve for wetness if the saturated concentration value is not dependent on temperature or time. However, certain components of electronic packages are highly dependent on temperature under reflow process [6]. Most polymer materials in electronic packages have lower glass transition temperature than the reflow temperature. Hence, their C_{sat} values become time dependent during the reflow process.

The time dependency of saturated concentration requires special treatment because the wetness equation is not directly analogous to the standard diffusion equation. A finite element model of multi-material system using wetness approach under transient loading was first proposed by Wong et al. [7]; it is referred to as "*piecewise normalization*" approach. However, it requires several load steps and complex algorithms. In order to achieve computational efficiency and easy implementation, Wong [8] introduced an alternative approach referred to as "*internal source*" approach. This approach invokes temperature dependency of saturated concentration as an internal source function, and its time dependency is approximated with the backward Euler method. However, its solution with FEM is highly dependent on number of iterations performed during each time step. Recently, Wong and Park [9] revised the internal source technique, and removed the requirement for iterations.

An alternative to the FEM is peridynamics. It is originally introduced as the reformulation of continuum mechanics equations by Silling [10] to predict cracking and damage evolution. Peridynamics (PD) is extremely suitable to model discontinuities such as cracks and interfaces because its governing equation does not include any spatial derivatives; thus remaining valid regardless of discontinuities. Moreover, it is not limited to the solution of mechanical field equations and can be used to describe other governing field equations as presented by Madenci and Oterkus [11].

Hence, this study presents a peridynamic wetness modeling to determine moisture concentration in electronic packages with complex structure of dissimilar materials. It accommodates interfaces naturally while considering the effect of different material properties. Also, it does not require additional continuity conditions of moisture concentration across the interface. Moreover, the solution to peridynamic equation of wetness does not require iterations during each time step even with time dependent C_{sat} values. Numerical results demonstrate that peridynamics can accurately predict the moisture diffusion in electronic packages during absorption and desorption.

2. Classical moisture diffusion equation

As derived by Wong [8], the transient moisture diffusion can be expressed as

$$\dot{C}(\mathbf{x},t) = D(t)\nabla^2 C(\mathbf{x},t) + \Theta_m(\mathbf{x},t) \tag{1}$$

where C is the moisture concentration, Θ_m is the internal source function, D is the diffusivity, ∇^2 is the Laplace operator, and 'dot' denotes time derivative. The saturated concentration, C_{sat} is defined as

$$C_{sat} = SP_{VP} \tag{2}$$

where S is the solubility and P_{VP} is the ambient vapor pressure. The diffusivity and solubility can be defined through the Arrhenius law as

$$D(t) = D_0 e^{\left(\frac{-E_D}{RT(t)}\right)} \tag{3a}$$

and

$$S(t) = S_0 e^{\left(\frac{E_S}{RT(t)}\right)} \tag{3b}$$

in which D_0 is the diffusivity factor, E_D is the activation energy of the diffusivity, S_0 is the solubility factor, E_S is the activation energy of the solubility, R is the universal gas constant (R = 8.3145 J/Kmol), and T represents temperature.

Finite Element Method (FEM) is capable of solving for the moisture concentration, Eq. (1) if the domain is homogeneous with nodal continuity. However, it breaks down in the case of a nonhomogeneous domain in which moisture concentration is not continuous at the interface of different materials. In order to resolve this issue, Wong et al. [5], introduced a normalized parameter called "wetness" as

$$w = \frac{C}{C_{sat}} \tag{4}$$

The interface continuity can be assumed in the form

$$w_1 = \frac{C_1}{C_{sat1}} = w_2 = \frac{C_2}{C_{sat2}} \tag{5}$$

where the subscripts indicate different materials on both sides of the interface. Therefore, the interface continuity of these normalized variables is automatically satisfied. The value of unity indicates full saturation, and a zero value indicates no moisture concentration. The wetness approach ensures the equalization of chemical potentials at the interface of dissimilar materials which is not satisfied by using a direct concentration approach [8].

With the "wetness" parameter, Eq. (1) can be recast for time independent C_{sat} as

$$\dot{w}(\mathbf{x},t) = D(t)\nabla^2 w(\mathbf{x},t) \tag{6}$$

This equation can be solved readily by employing the thermal-wetness analogy as proposed by Wong et al. [5]. Its solution can be readily achieved by existing techniques such as any finite element method.

If C_{sat} is time (temperature) dependent, Eq. (1) can be recast in terms of the "wetness" parameter as [8]

$$C_{sat}(t)\dot{w}(\mathbf{x},t) = D(t)C_{sat}(t)\nabla^2 w(\mathbf{x},t) + \Theta_m(\mathbf{x},t) \tag{7a}$$

with

$$\Theta_m(\mathbf{x},t) = -w(\mathbf{x},t)\dot{C}_{sat}(t) \tag{7b}$$

However, the solution to this equation requires a special method such as the "*piecewise normalization*" approach by Wong et al. [7] or the "*internal source*" approach by Wong [8]. The latter approach is straightforward and easy to implement. However, it is highly dependent on the number of iterations performed during each time step because $\Theta_m(\mathbf{x},t)$ is assumed as constant between the consecutive time steps. The diffusivity parameter and the saturated concentration are also updated in each time step as part of this procedure.

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