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Vapor Pressure Modeling for PEMs Subjected to Lead-free Solder Reflow Profile

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ABSTRACT

The moisture poses a significant threat to the reliability of plastic encapsulated microelectronics (PEM) components and can be attributed as being one of the principal causes of many premature package failures. In recent years, the research efforts on moisture absorption issues in PEMs have been quite intensive and different techniques have been proposed. Among these achievements, the study of vapor pressure, which originates from the accumulation of moisture along material interfaces and is responsible for the well-known popcorn cracking, presents the most technical challenges and the desired solution remains lacking. It is noted that the condition due to vapor pressure is exacerbated for Pb-free solders since the peak temperature used in Pb-free solder reflow process is higher (235°C-265°C). This paper aims to develop an accurate, universal, and practical modeling technique to study the dynamic vapor pressure buildups at the interfaces in plastic packages during Pb-free solder reflow process. The existing vapor pressure modeling techniques were investigated and reviewed, and the most appropriate scheme was evaluated, improved and employed in this paper. The proposed vapor pressure modeling scheme provides the dynamic vapor pressure required for the reliability-related fracture and interface analysis of plastic packages. It has considerable value for developing new materials, innovative structures and effective protection methods for enhancing the performance and reliability of plastic packages.

INTRODUCTION

Plastic encapsulated microelectronics (PEM) components (often called plastic packages), due to many technical, economic, and logistical reasons, have attracted more than 95% of the market share of worldwide microcircuit sales. In spite of the wide application, one critical problem with the plastic packages is that the molding compounds used in the packages are hydrophilic and absorb moisture when exposed to the environment [1][2]. The moisture absorbed and trapped in plastic packages poses a significant threat to the reliability of PEMs. For instance, the presence of moisture in the packages alters thermal stress through altering thermo-mechanical properties, induces hygroscopic stress through inducing hygroscopic swelling, reduces interfacial adhesion strength, induces corrosion, and induces vapor pressure that responsible for the eventual popcorn cracking, and so on. Consequently, moisture can be attributed as a principal cause of failures of many plastic packages. In fact, plastic packages have encountered formidable challenges in gaining acceptance for use in military applications.

In recent years, the research efforts on moisture absorption and effect issues in plastic packages have been very intensive and different techniques have been proposed, such as experimental schemes to determine hygroscopic properties of polymeric materials (diffusion coefficient, solubility, hygroscopic swelling coefficient, etc.) and computational modeling schemes to depict moisture absorption behavior, characterize relevant properties and predict hygroscopic stresses. Among these research efforts, the study of vapor pressure, which originates from the accumulation of moisture along material interfaces and is responsible for the well-known popcorn cracking at high temperatures [3]-[7], presents the most technical challenge and the desired solution remains lacking. It is noted that such a study is highly demanded as electronic technologies evolve:

- Lead-free solders are being used in modern electronics. During solder reflow process, the packages are subjected to higher temperature (235°C-265° C) than the conventional one (215°C). This leads to higher vapor pressure (up to 60% or higher) and makes the critical situation due to vapor pressure exacerbated.
- As the elements and structures involved in high-end electronics devices are made smaller to enhance the electrical performances, the vapor pressure brings more serious mechanical reliability issues to the electronics not only during manufacturing process but also at working conditions.

Due to above reasons, the study of vapor pressure modeling has become of utmost importance to assess reliabilities of microelectronics products.

EXISTING TECHNIQUES

There are three mechanisms that contribute to water moisture penetration at the interfaces in plastic packages [8][9]:

- Bulk diffusion – Bulk diffusion is the result of the continual thermal motion of atoms, molecules, and particles from an area of high concentration to an area of low concentration. Due to bulk diffusion, a typical plastic packaging material such as epoxy formulation can absorb 1%-7% weight in moisture. In addition to the typical Fickian bulk diffusion behavior, non-Fickian behavior can occur in some plastic packaging systems.
- Wicking – Moisture may penetrate into the plastic packages through wicking along the material interfaces.
- Capillary – Capillary action is similar to wicking, the distinction lies in that capillary action is associated with micro-cracks or channels present inside the plastic packaging materials. The voids and cracks are normally formed by the addition of fillers in polymer composites.

Experimental evidence shows that bulk diffusion is the dominant mechanism for moisture transportation into plastic packages, and all the existing vapor pressure modeling schemes are based on bulk diffusion. This proposed research will put emphasis on modeling based on bulk diffusion as well.

The existing vapor pressure modeling techniques typically fall into two primary categories: one is the approach based on saturation and the other is the approach based on mass (moisture) diffusion analysis. The saturation based modeling usually involves a simple approach and yields overestimated results, whereas the diffusion-based modeling is generally more rigorous, complex, and computation-intensive.

According to the equation of state of the water vapor, the vapor pressure within the delamination is dependent on the temperature, the volume of the delamination and the mass of the water vapor within the delamination. It is noted that the volume of the delamination is a function of both the pressure and the temperature in the delamination, and the mass of the water vapor in the delamination is governed by the pressure, the temperature and the duration of diffusion. Consequently, the terms required to determine the vapor pressure are coupled with each other. Based on this consideration, Kitano [10] proposed the first attempt on dynamic vapor pressure modeling, where the vapor pressure along a delaminated interface at each time step can be evaluated using a fixed-point iteration technique. Since Kitano's model is based on a 1D analysis, it is relatively simple and finite element analysis is not required (computer is needed though). However, the assumptions and simplifications involved in this approach substantially restrict its application.

To cope with the over-simplification issue with Kitano's model, Tay and Lin [11] performed a 2D finite element analysis (FEA) implementation of Kitano's algorithm. In the new approach, the temperature and moisture concentration are determined by FEA, and the dynamic vapor pressure within the delamination is evaluated through iteration. Figure 1 illustrates a flowchart of the 2D modeling, which contains a 2D description of Kitano's original algorithm. Recently, Koh [12] and Wong *et al.* [13] further introduced a decoupling algorithm to achieve a fully automated 2D FEA modeling using the macro functions provided by ANSYS software.

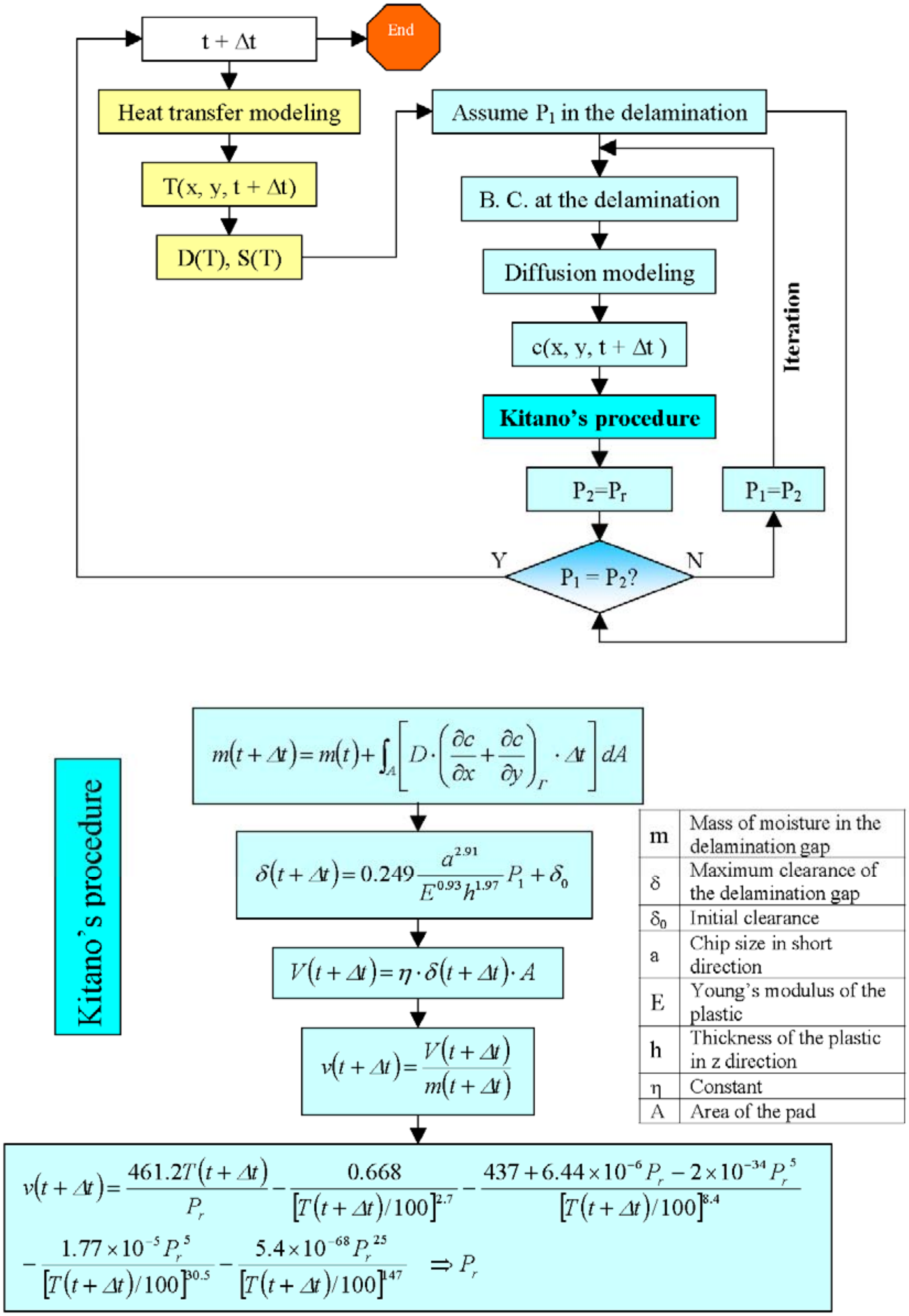
Kitano's original and improved approaches were claimed to have rigorous theoretical explanation and provide reliable results due to the use of FEA; however, a careful investigation reveals that there are a few problems with the approaches: (1) In Kitano's procedure, the volume of the delamination is obtained using a governing formula that was initially an approximate for a specific structural configuration [10] (as seen from the algorithm description in Figure 1). However, such a handling of volume determination is invalid for most plastic packages. (2) The volume change due to thermal expansion and hygroscopic swelling has not been considered. It has been realized that they, especially thermal expansion, must be incorporated into the modeling to obtain the volume change of delamination for an accurate diffusion analysis and vapor pressure determination. (3) For the design and failure analysis of modern complex plastic packages in practice, 3D modeling is normally required to ensure the accuracy. (4) The iteration is very time-consuming. To obtain a reliable FEA diffusion modeling, the time increment in diffusion analysis must be set very small to ensure small variations of diffusion parameters. Otherwise, the analysis will not converge correctly. One associated problem here is that unlike the finite element analysis of conventional problems, the moisture diffusion analysis must use extremely small element size to satisfy the convergence criterion. Consequently, the analysis requires very long calculation time. For the modeling of a commercial package with complex configuration, it may take several months or years to complete the analysis even a high-performance PC with the multi-core processor is utilized. This shortcoming highly limits the practical application of the iteration-based modeling. (5) ANSYS software makes decoupling algorithm possible for a fully automated modeling; however, the modeling has to employ the heat transfer module because ANSYS does not provide a generic mass diffusion analysis capability. It has been recently noticed that the usage of thermal-moisture analogy is only valid for single material system or constant temperature conditions [14]. This implies that ANSYS should not be adopted for moisture diffusion modeling of plastic packages. To the best of authors' knowledge, ABAQUS is currently the only finite element software that provides a general mass diffusion analysis suitable for broad applications; furthermore, even ABAQUS is not capable of handling the spatially nonuniform temperature distributions and must be used with extreme care to avoid such a case [14][15].

PROPOSED TECHNIQUE

One of the primary differences between the proposed approach and Kitano's model (original or improved) is that finite element structural modeling is employed to determine the dynamic volume of the delamination along the material interfaces. The Kitano's procedure (can be seen in Figure 1) uses specific governing equations for volume calculation, which is valid for certain thin and simple packages only. With finite element structural analysis, together with thermal expansion and hygroscopic swelling involved, the proposed modeling becomes rigorous and suitable for any types of practical packages, either complex or simple. The proposed technique is illustrated in Figure 2. It is noteworthy that although the flowchart may give an impression that the proposed technique is a simple extension of Kitano's technique, the proposed technique and the existing one actually have fundamental distinctions since the core units are different and all the limitations in existing technique can be well coped with.

The proposed technique eliminates the time-consuming iteration through self-adjusting the vapor pressures during the analysis, and the computational efficiency can be significantly enhanced due to the non-iterative nature of the process. The scheme is described as follows. In the proposed modeling analysis, the initial pressure is set to be the normalized concentration at the delamination interface. The basic principle of the new approach is that an overestimated (underestimated) pressure will impede (aid) the moisture diffusion into the delamination, thus the pressure at the next time increment can be self-adjusted. With small time increments (this is also desired for high accuracy purpose), the time-consuming iteration can be eliminated while keeping the analysis accurate.

Since the temperature is time dependent, diffusion properties of materials are temperature dependent, and vapor pressure boundary conditions are determined by time, temperature, mass and pressure of moisture vapor, the modeling at each time increment involves a complex procedure. ABAQUS package itself cannot directly handle an entire modeling. An external computer program must be developed to call ABAQUS to perform corresponding analysis for each time increment. The external program can read the calculation results from the current step and generate input data (e.g., initial values, dynamic boundary conditions, etc.) for the next time increment. In this paper, the modeling control module has been packed into a generic Unix/Linux/Windows program.



$$m(t+\Delta t)=m(t)+\int_A\left[D\cdot\left(\frac{\partial c}{\partial x}+\frac{\partial c}{\partial y}\right)_r\cdot\Delta t\right]dA$$

$$\delta(t+\Delta t)=0.249\frac{a^{2.91}}{E^{0.93}h^{1.97}}P_1+\delta_0$$

$$V(t+\Delta t)=\eta\cdot\delta(t+\Delta t)\cdot A$$

$$v(t+\Delta t)=\frac{V(t+\Delta t)}{m(t+\Delta t)}$$

$$v(t+\Delta t)=\frac{461.2T(t+\Delta t)}{P_r}-\frac{0.668}{[T(t+\Delta t)/100]^{2.7}}-\frac{437+6.44\times10^{-6}P_r-2\times10^{-34}P_r^{5}}{[T(t+\Delta t)/100]^{8.4}}-\frac{1.77\times10^{-5}P_r^{5}}{[T(t+\Delta t)/100]^{30.5}}-\frac{5.4\times10^{-68}P_r^{25}}{[T(t+\Delta t)/100]^{147}}\Rightarrow P_r$$

m	Mass of moisture in the delamination gap
δ	Maximum clearance of the delamination gap
δ_0	Initial clearance
a	Chip size in short direction
E	Young's modulus of the plastic
h	Thickness of the plastic in z direction
η	Constant
A	Area of the pad

Figure 1. 2D implementation of Kitano's vapor pressure modeling scheme

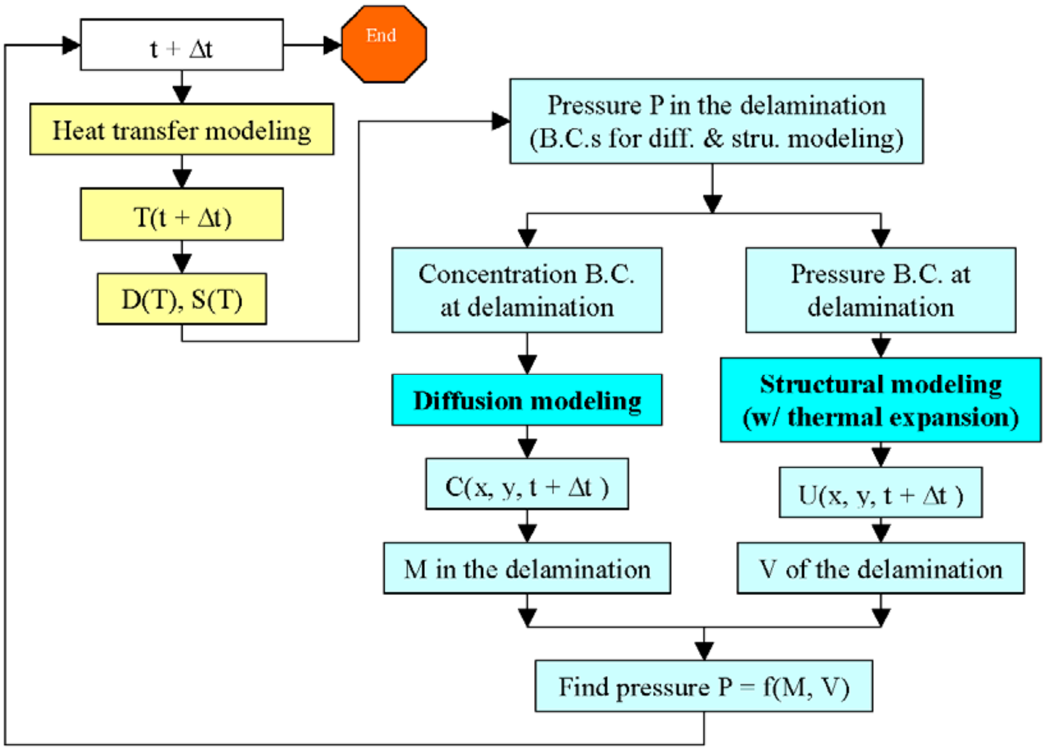


Figure 2. Proposed vapor pressure modeling scheme

SIMULATION

A package example illustrated in Figure 3 is investigated in this paper to study the effect of solder reflow profile on the vapor pressure within the package. The package is put in pre-moisture conditioning of 85°C/85%RH for 34 hours, and then is exposed to the two solder reflow conditionings as shown in Figure 4. The peak reflow temperatures are 205°C and 238 °C for Sn-37Pb and Pb-free profiles, respectively. The results obtained from the proposed fast modeling analysis are presented in Figure 5 where the peak vapor pressure values are 0.80 MPa and 1.10MPa for Sn-37Pb and Pb-free profiles respectively. The simulation indicates that small increase of solder reflow temperature can result in large vapor pressure increase. Consequently, the relevant mechanical effect must be carefully investigated in further mechanics analysis.

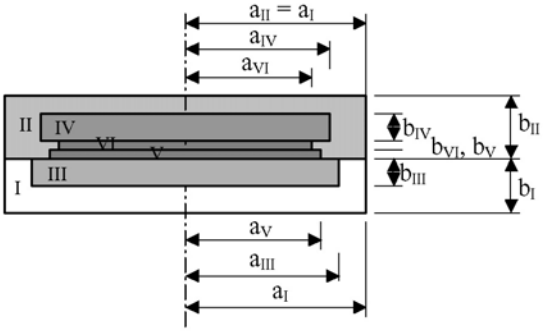


Figure 3. A package

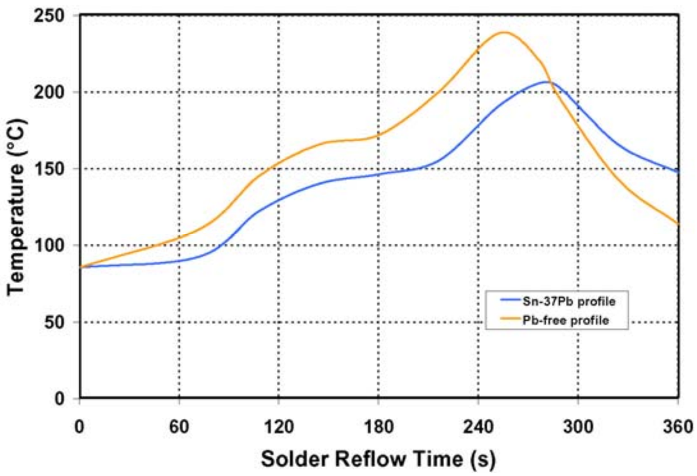


Figure 4. Solder reflow profiles

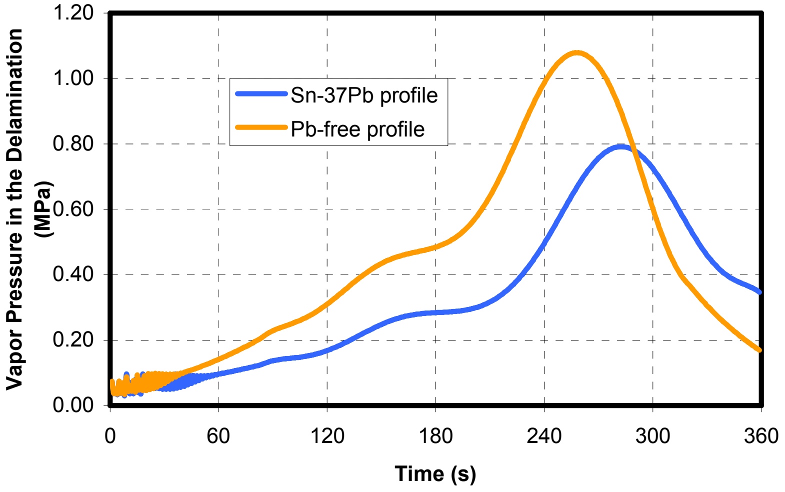


Figure 5. Vapor pressures for different solder reflow profiles

CONCLUSION

An accurate, universal, and practical vapor pressure modeling technique to study the dynamic vapor pressure buildups at the interfaces in PEMs during Pb-free solder reflow process is presented. The proposed technique is capable of providing the dynamic vapor pressure required for the reliability-related fracture and interface analysis of plastic packages. It may have considerable value for developing new materials, innovative structures and effective protection methods for enhancing the performance and reliability of plastic packages.

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