Microelectronics International

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Jae B. Kwak Seungbae Park

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Jae B. Kwak
Global Technology Center, Samsung Electronics, Suwon-si, South Korea, and
Seungbae Park
Department of Mechanical Engineering, State University of New York at Binghamton, Binghamton, New York, USA

Abstract

Purpose – The purpose of this paper was to study the combined effect of hygro and thermo-mechanical behavior on a plastic encapsulated micro-electro-mechanical systems (MEMS) package during the reflow process after exposed to a humid environment for a prolonged time. Plastic encapsulated electronic packages absorb moisture when they are subjected to humid ambient conditions.

Design/methodology/approach – Thus, a comprehensive stress model is established for a three-axis accelerometer MEMS package, with detailed considerations of fundamentals of mechanics such as heat transfer, moisture diffusion and hygro-thermo-mechanical stress. In this study, the mold compound is considered to be the most critical plastic material in MEMS package. Other plastic components of thin film materials can be disregarded due to their small sizes such as die attach and Bismaleimide Triazine (BT) core, even though they are also susceptible to moisture. Thus, only the moisture-induced properties of mold compound were obtained from the proposed experiments. From the desorption measurement after preconditioning at 85°C/85 per cent relative humidity (RH), the saturated moisture content and diffusivity were obtained by curve fitting the data to Fick's equation. In addition, a new experimental setup was devised using the digital image correlation system together with a precision weight scale to obtain the coefficient of hygroscopic swelling (CHS) at different temperatures.

Findings – The experimental results show that the diffusion coefficient of mold compound material follows Arrhenius equation well. Also, it is shown that the CHS of mold compound increases as temperature increases. Experimentally obtained moisture properties were then used to analyze the combined behavior (thermo-hygro-mechanical) of fully saturated MEMS package during the reflow process using a finite element analysis (FEA) with the classical analogy method. Finally, the warpage and stresses inside the MEMS package were analyzed to compare the effects of hygroscopic, thermal and hygro-thermo-mechancal behaviors.

Originality/value – In this study, unlike the other researches, the moisture effects are investigated specifically for MEMS package which is relatively smaller in scale than conventional electronic packages. Also, as a conjugated situation, MEMS package experiences both humid and temperature during the moisture resistance test. Thus, major objective of this study is to verify stress state inside MEMS package during the reflow process which follows the preconditioning at 85°C/85 per cent RH. To quantify the stresses in the package, accurate information of material properties is experimentally obtained and used to improve modeling accuracy.

Keywords Micro-electro-mechanical systems (MEMS), Microelectronics packaging, Advanced packaging, Chip on board (COB)

Paper type Research paper

1. Introduction

The problem of moisture absorption and subsequent package failure at elevated temperature is an issue to the reliability of microelectronic devices (Zhang *et al.*, 2006; Fan, 2008). The mold compound of a micro-electro-mechanical systems (MEMS) package absorbs moisture when it is exposed to humidity at elevated temperature. The absorbed moisture in the mold compound influences the mechanical properties. Then, during the reflow after moisture absorption, the composite nature of MEMS package causes internal stresses in the package. These internal stresses may be sufficient to shift device output (Zhang *et al.*, 2007), and either delaminate or crack inside the package. These failure mechanisms could be accelerated by deformation mismatch between adjacent polymeric materials caused by both thermal expansion and hygroscopic swelling. The purpose of this paper is to study the combined effect of moisture and temperature on the reliability of MEMS packages.

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Microelectronics International
32/1 (2015) 8–17

[ISSN 1356-5362]
[DOI 10.1108/MI-04-2014-0014]

The authors would like to thank Xin Zhang, Analog Devices, Inc. and all members of Opto-Mechanics and Physical Reliability Lab, Binghamton University for their material and intelligent support during this study.

Received 9 April 2014
Revised 2 August 2014
Accepted 20 September 2014

Especially, hygro-thermally induced stress effects are investigated for MEMS sensors encapsulated by polymers.

In general, there are three types of failure mechanisms caused by moisture ingression inside the structural integrity of electronic packages. They are delamination, popcorn failure and electrochemical migration which are often referred as corrosion. The first two failures have very similar root cause. The penetrated moisture inside an electronic package condenses in micro-voids or pores in polymer materials and along the interfaces between adjacent components. Then, vaporization of condensed moisture results in a high vapor pressure under elevated temperature environment. Also, the polymer materials become compliant (soften), and the interfacial adhesion strength significantly drops due to the heated moisture above the glass transition temperature (T_g). In addition, there are conjugated stresses induced due to the hygro and thermo-mechanical deformation interacting inside the package. This combined effect causes delamination failure. Particularly, if the high vapor pressure builds up at the cracked interface in a short time, the popcorn failure is known to occur.

There have been major researches dealing with thermo-hygro-mechanical stresses in various types of integrated circuit package. Galloway and Miles (1997) mainly dealt with moisture effect leading to popcorn failure in plastic ball grid array package during reflow process and solder pot dip test. Zhou and Law (2008) took analytical approach to deal with the effect of non-uniform moisture in obtaining coefficient of hygroscopic swelling (CHS) and applied to study the stresses of underfilled flip-chip ball grid array joints under highly accelerated stress test environment. Also, Hsu and Hsu (2009) studied the delamination failure associated with moisture on finger printer package by obtaining hygro-material property. Tsai *et al.* (2007) obtained CHS for non-conductive film material based on Timoshenko's bi-material theory by using Twyman–Green interferometry and applied the result to the stress analysis of the chip-on-glass package. Kim and Kong (2006) studied the reliability of the flip-chip, chip-scaled package with gold bump at the moisture resistance test (MRT) reflow temperature by obtaining and using the moisture property of the mold compound. Also, Yoon *et al.* (2009) investigated the moisture properties of anisotropic conductive adhesion package and analyzed its stress under humid environment. The above literatures introduce various experimental methods to obtain moisture properties, especially the CHS, for various types of materials. And for the analysis of the transient state of moisture and stresses using commercial finite element analysis (FEA) programs, the classical analogy is applied to FEA's thermal transition model.

In this study, unlike the above researches, the moisture effects are investigated specifically for MEMS package which is relatively smaller in scale than conventional packages. Thus, vapor pressure can be ignored assuming there is no initial delamination or large void in the package, which are considered as defects in MEMS package manufacturing. A typical situation in which an MEMS package experiences both humid and temperature is the MRT where the packages are subjected to the reflow process after moisture preconditioning. Thus, one objective of this study is to verify stress state inside MEMS package during the reflow process which follows the preconditioning at 85°C/85 per cent relative humidity (RH). As a preconditioning, 85°C/85 per cent RH is considered because it is one of standard reliability tests for MEMS package related with temperature and humidity. To quantify the stresses in the package, accurate information of material properties is required to improve modeling accuracy. Because the thermal properties of materials used in the package are already well investigated (Zhang *et al.* (2007), this paper discusses an experimental procedure to determine the moisture properties of mold compound used in the package. The saturated moisture concentration and moisture diffusivity were determined by measuring the weight gain/loss during the moisture absorption/desorption process at different temperatures. Conventionally, thermo-gravimetric analysis (TGA) and thermo-mechanical analyzer (TMA) are used to obtain CHS during the desorption process. However, there are possible error sources that produce overestimation or underestimation in CHS calculation. Two major issues are the non-uniformity of moisture across the specimen and the moisture loss due to evaporation at the high temperatures during the desorption measurement. Zhou and Law (2008) proposed and suggested an experimental procedure and specimen geometric factor to minimize errors. Zhang *et al.* developed digital image correlation "(DIC) quick scanning method" to obtain corrected CHS considering both error sources (Zhang *et al.*, 2010; Park *et al.*, 2009). In this paper, a new experimental method was developed and introduced for obtaining CHS effectively.

The DIC method, a non-contact full field deformation measurement system, was used to measure in-plane and out-of-plane displacements. Together with DIC, a precision scale was used to obtain the strain and moisture loss simultaneously during the desorption process which results in CHS. In addition, warpage measurement for dried MEMS package using DIC was performed to validate thermo-mechanical FEA model. Then, by implementing the obtained moisture properties into FEA thermal diffusion model using the classical analogy, the transient moisture diffusion analysis and hygro-thermo-mechanical stress analysis were carried out.

Then, a correlation between thermal and hygroscopic behavior of MEMS package could be determined by FEA simulation. For FEA analysis, the heat transfer modeling module can be used for the transient moisture diffusion model because they are analogous. Consequently, the hygroscopic swelling strain can be treated as an additional thermal strain superimposed to the thermal strain. Also, in an isothermal case with uniform moisture concentration, an equivalent coefficient of thermal expansion can be defined for the combined strains of both the thermal and hygroscopic swelling strains in an integrated thermal and hygroscopic analysis.

As mentioned, the particular interest of our investigation is the stress pattern and distribution inside the MEMS package, so that it can be compared between the presence and absence of moisture effect. Thus, the major focus is on the impact of combined thermal and hygro-mechanical stresses. A series of comprehensive parametric studies can be performed later using the validated FEA model. Thus, this study provides a good guideline to designing MEMS packages with low induced stresses, and also gives an insight into the failure mechanism associated with both thermal loading and moisture absorption.

2. Theory

In this study, the moisture, thermal, thermo-mechanical and hygro-mechanical models are integrated into a thermo-hygro-mechanical constitutive model. The following framework is to describe the theories of these models.

2.1 Heat transfer

The transient thermal diffusion, heat transfer, can be defined as following equation:

$$\frac{\partial T}{\partial t} = \alpha_T \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right), \tag{1}$$

where T (K) is the absolute temperature, and:

$$\alpha_T = \frac{K}{\rho C_p} \tag{2}$$

is the thermal diffusivity, where K is the thermal conductivity: C_p is the specific heat and ρ is the material density.

2.2 Moisture diffusion, concentration and wetness

Moisture diffusion would occur when a mold compound and other polymeric materials are exposed to humid environment. This transient diffusion for an isotropic ($D_x = D_y = D_z$) material can be modeled by Fick's second law and is described by the following equation:

$$\frac{\partial C}{\partial t} = D \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2} \right), \tag{3}$$

where C (mg/mm^3) is the local moisture concentration and t is the time. For a 3-D rectangular solid, the equation (3) can be solved using the standard separation of variable method, and it yields an expression for the local moisture concentration as a function of time as derived in equation (4). Thus, by curve fitting the moisture loss data (m(t)) obtained during desorption measurement to equation (4), the moisture diffusivity, D (mm^2/s) can be determined:

$$\frac{m(t)}{m_{sat}} = 1 - \frac{512}{\pi^6} \sum_{l=0}^{\infty} \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} \frac{\exp(-Dt/L_{eqv}^2)}{(2l+1)^2(2m+1)^2(2n+1)^2},$$
$$L_{eqv}^2 = \left\{ \left[\frac{(2l+1)\pi}{x_0} \right]^2 + \left[\frac{(2m+1)\pi}{y_0} \right]^2 + \left[\frac{(2n+1)\pi}{z_0} \right]^2 \right\}^{-1}, \tag{4}$$

where m(t) is the instantaneous mass of the specimen, m_{sat} is the saturated mass, L_{eqv} is an equivalent length and x_0, y_0 and z_0 are the length, width and thickness, respectively.

The moisture diffusivity is static and constant during moisture absorption and desorption, which generally follows the Arrhenius equation as below:

$$D = D_0 \exp\left(\frac{-Q}{RT} \right), \tag{5}$$

where D_0 is the diffusivity coefficient, Q (eV) is the activation energy, R (8.617E-5 eV/K) is the Boltzmann constant and T(K) is the absolute temperature.

As another important moisture property, C_{sat}, the saturated moisture concentration is defined as below:

$$C_{sat} = \frac{m_{sat}}{V}, \tag{6}$$

where V is the total volume of the specimen and m_{sat} is the saturated mass of moisture over the specimen. For many polymers used in microelectronic packaging, the most conventional hypothesis is that the saturated concentration (C_{sat}) is more dependent on the RH than temperature, although several exceptions are reported (Yoon *et al.*, 2009; Bao and Yee, 2002; Fan *et al.*, 2009). According to Fan *et al.*, C_{sat} has strong dependency on the free volume change, and free volume change increases with temperature increase, especially above T_g. Thus, C_{sat} may increase as temperature increases.

Although heat transfer is analogous to moisture diffusion, there is one difference which is a way to treat discontinuity at the interface between two different materials for moisture diffusion. Galloway and Miles (1997) introduced a new dependent variable, partial vapor pressure (also known as normalized concentration) to solve this computational issue by including solubility (Kim and Kong, 2006). However, the discontinuity at the interface is disregarded in this study because only mold compound is considered to have hygro-properties. In addition, moisture wetness, w, as the field variable, can be defined as below:

$$w = \frac{C}{C_{sat}}, 0 \le w \le 1 \tag{7}$$

where C_{sat} is the fully saturated moisture concentration. Thus, w = 0 is totally dried and w = 1 is fully saturated (wet). Thus, then equation (3) can be used to moisture transient analysis during reflow process and rewritten as the following:

$$\frac{\partial w}{\partial t} = D \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) \tag{8}$$

2.3 Combined stress analysis

The CHS is defined as a measure of change in material strain with moisture concentration. When there is a mismatch of the CHS among various materials in a package, the hygro-mechanical stress is induced. The hygroscopic strain is defined as $\varepsilon_h = \beta C$, where β is the CHS, just as the thermal strain is defined as $\varepsilon_T = \alpha \Delta T$, where α is the CTE. Therefore, the hygroscopic constitutive relation is analogous to the thermo-mechanical constitutive relation. And the total strain due to thermo-hygro-mechanical effect can be described by $\varepsilon = \varepsilon_h + \varepsilon_T = \beta C + \alpha \Delta T$. Here, we consider a special case, where the temperature and moisture across a polymer material in the package are uniform, although the moisture concentration may not be uniform across the entire package. Then, in the FEA implementation, the hygroscopic strain can be treated as additional thermal strain. Therefore, in this study, the thermo-hygro-mechanical analysis was conducted using linear superposition in the commercial numerical software, ANSYS.

3. The experimental procedure and results

3.1 Test vehicle

The essential properties required for the moisture diffusion analysis in the FEA are diffusivity and saturated moisture concentration. In addition, CHS is required for the hygro-mechanical stress analysis. The particular MEMS package used in this study is supplied in a 14 lead land grid array (LGA) type package, which is small and thin shaped with dimensions of 5 mm × 3 mm × 1 mm. As shown in Figure 1, the component materials of MEMS package are mold compound, MEMS die/application-specific integrated circuit (ASIC) and BT core substrate.

Although, the thermal properties of these materials are well known, the hygro-properties of mold compound, which is considered major portion in this package, are not well investigated. Therefore, in this study, the experiment to obtain hygro-properties for mold compound is mainly discussed.

3.2 Characterization of hygro-material properties

To characterize diffusivity (D), saturated moisture concentration (C_{sat}) and CHS at various temperatures, DIC and precision weight scale were used during absorption and desorption process. A number of identical specimens of mold compound were prepared with dimensions of 7 mm × 7 mm × 1 mm. All specimens were placed in the constant thermal-moisture environment at 85°C/85 per cent RH (joint electron device engineering council (JEDEC) Level 1) until they are fully saturated. As shown in Figure 2, it takes the specimens approximately 38 hours to be fully saturated during absorption process.

3.2.1 Diffusivity and saturation

The procedure for obtaining D at various temperatures is as follows:

- Place each saturated specimen in 85°C, 95°C, 110°C, 125°C and 145°C isothermal environment.
- Measure weight loss for each specimen at specific time intervals (expressed as dots in Figure 3).

Figure 1 Components of LGA 5 mm × 3 mm × 1 mm package

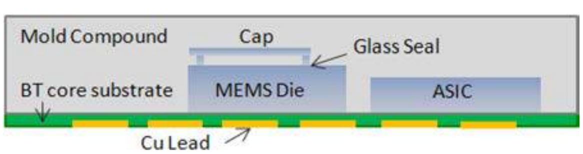


Figure 2 Moisture weight gain plot at 85°C/85 per cent RH

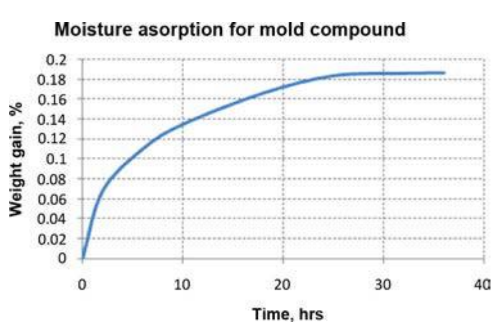
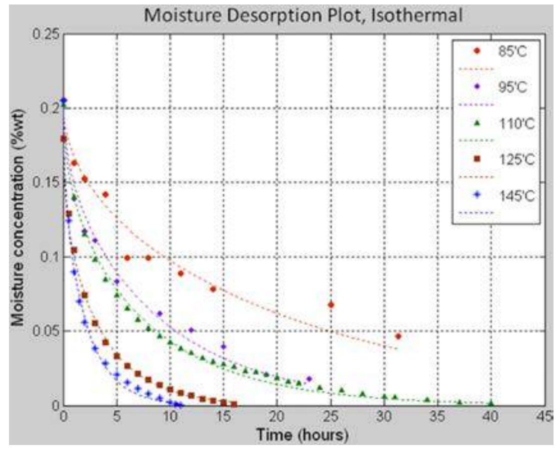


Figure 3 Moisture concentration with respect to time and curve fitting at various temperatures



- Curve fit the weight loss data to equation (4), and calculate the concentration over volume of the rectangular specimen (expressed as dash line in Figure 3).
- The results are shown in Figure 3.

After obtaining each diffusivity value, it can be again plotted with respect to temperature as shown in Figures 4 and 5. It clearly

Figure 4 Moisture desorption diffusivity with respect to temperatures

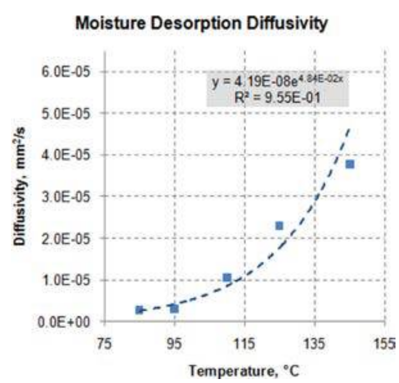
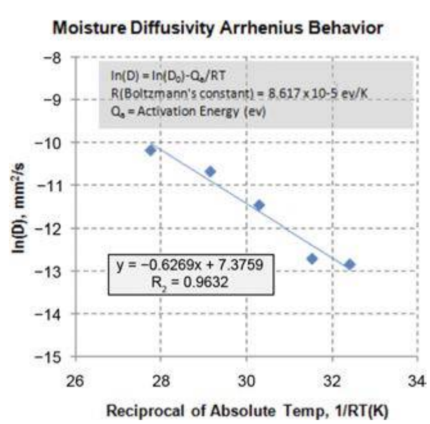


Figure 5 Moisture desorption properties following Arrhenius equation



shows that the result follows Arrhenius equation, equation (5). From the result shown in Figure 3, the saturated moisture concentration appears to be influenced by temperature because the rate of volume change in mold compound is susceptible for temperature as previously mentioned. Based on the experimentally obtained C_{sat}, C_{sat}'s for other temperatures can also be estimated by an extrapolation as shown in Figure 6.

3.2.2 CHS (β)

Characterization of CHS is another important objective of this study. There are two major concerns in obtaining CHS at elevated temperatures. One is overestimation (up to 250 per cent) or underestimation (up to 27 per cent) of CHS by disregarding the effect of non-uniform moisture across the specimen during weight change measurement (Zhou and Law, 2008; Zhou, 2008). These errors are highly dependent upon specimen's shape and dimension (ratio of width and thickness) and duration of weight change measurement. According to Zhou's research, test specimen needs to have large ratio of width and thickness to reduce error, which suggests a thin and large plate shape. Also, specimens requiring longer period of desorption (> 800 minutes) can yield more accurate CHS values. Another concern is the moisture loss during heating up process before desorption measurement starts for high temperature. Zhang *et al.* developed "DIC quick scanning method" to deal with both effects of moisture loss and non-uniformity of moisture, which obtains CHS by matching the results of experiment (hygro-strain) and FEA (moisture concentration, strain) during desorption process. Thus, in this study, thin plate specimen and desorption measurement were selected based on these researches. Also, a new experimental setup shown in Figure 7(a) was developed for CHS measurements.

Using DIC in the new setup, full field hygro-strain changes were obtained. Also, a precision weight scale which has 0.01 mg sensitivity was used to precisely measure the weight changes during desorption. Unlike the other conventional method, such as the method using TGA and TMA which requires time to ramp up temperature prior to desorption measurements, the proposed method is to place the identical specimens in two pre-heated chambers and take the measurements simultaneously. Figure 7(b) shows an example of the temperature profile measured right after specimen was placed inside chamber. Because the chambers are already

Figure 6 C_{sat} trend associated with temperature

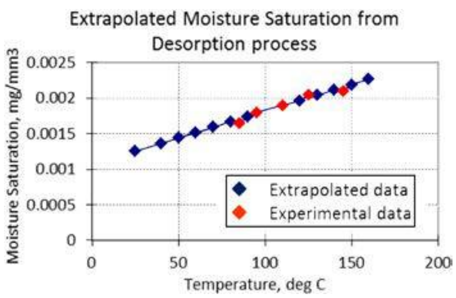
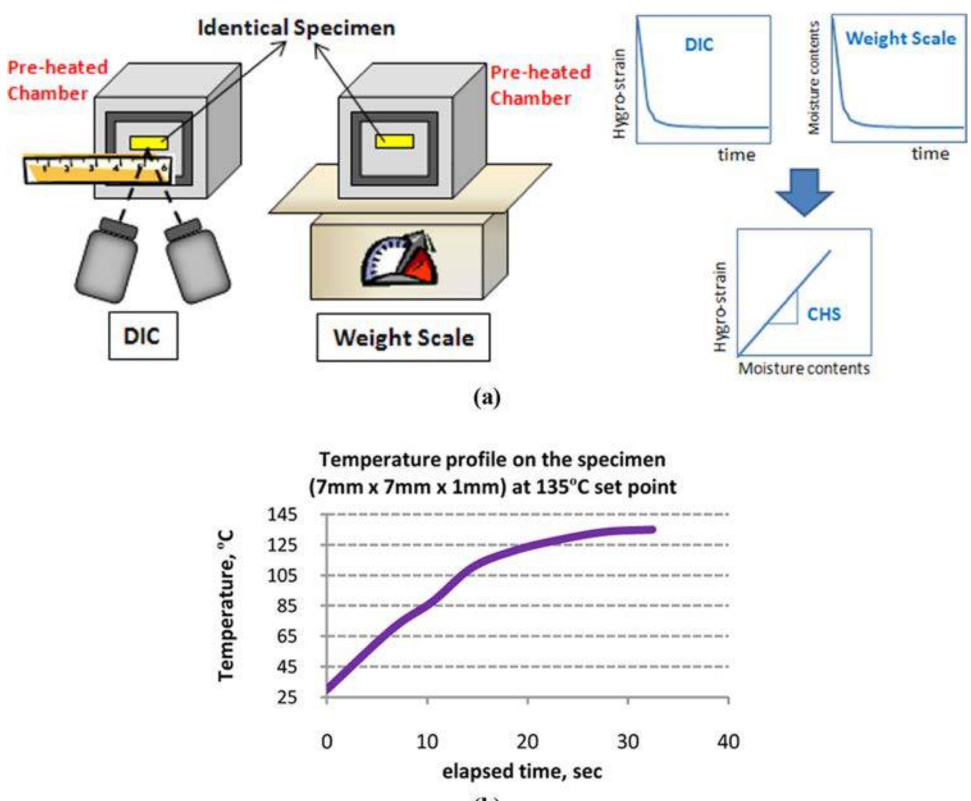


Figure 7 Proposed experimental method for obtaining hygro-material property



Notes: (a) Experiment setup; (b) initial temperature profile of the specimen pre-heated, it takes only 30 seconds to be isothermal at 135°C across this particular specimen. This implies that the initial moisture loss can be effectively reduced. In addition, there are other practical advantages in this proposed method. By using DIC, any size and shape of specimen can be used and uniformity of strain can be confirmed across the entire specimen surface during the measurement. However, TGA and TMA are normally restricted by size of specimen. Also, as TMA measures strain by reading dimension changes where the probe is located, strain measurement can be localized, and it is problem if the specimen undergoes non-uniform deformation.

As shown in Figure 8, DIC results show full field deformation map. This particular mold compound homogeneously shrinks during desorption process, which also implies isotropic moisture behavior. As illustrated in Figure 7(a), combined weight loss measurement (the first y-axis in Figure 8) with strain change (the second y-axis in Figure 8) at different isothermal conditions is resulted in linear slope which is CHS. This measurement was consequently performed at each temperature as mentioned previously.

Figure 9 shows the CHS calculation results at different temperatures. Overall, it shows as temperature increases, CHS also increases. However, there is significant CHS change in the trend observed between 100°C and 120°C around the T_g (~110°C). Figure 10 shows that the experimental data agree with those by DIC quick scanning method. Also, the result shows CHS increases with respect to temperatures below and above T_g. These hygro-material properties are implemented in FEA simulation for further investigation of moisture effect on MEMS package.

Figure 8 DIC and Weight scale result at 110 C from desorption

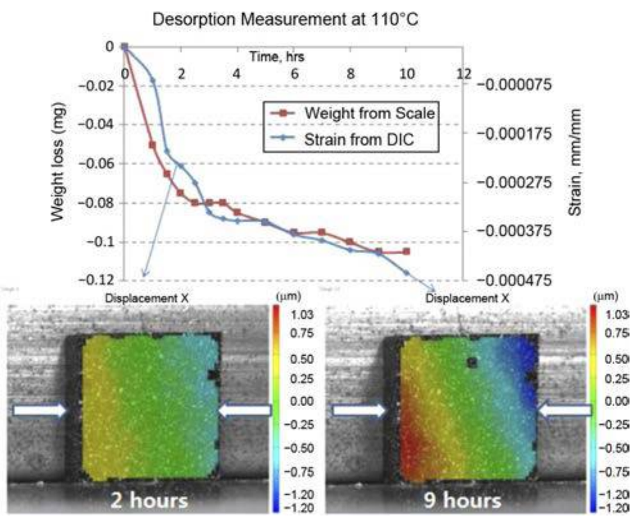
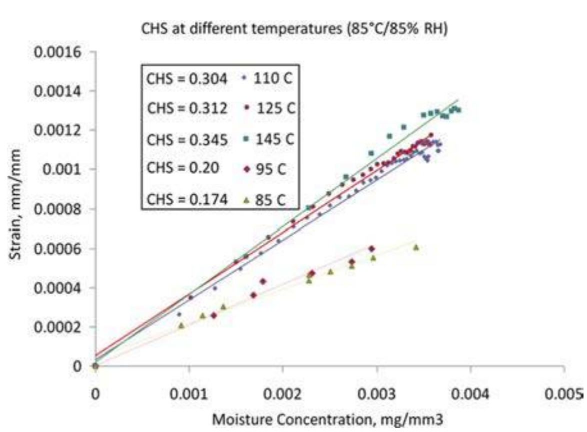


Figure 9 CHS at different temperatures



4. Warpage and stresses in MEMS package during reflow

4.1 FEA modeling and validation

Using ANSYS, a three dimensional FE model of MEMS package described in Figure 1 was generated. The modeled package was map-meshed by 3-D solid brick elements. Solid 45 was chosen as element type, and the constraint at the three corners of the model was applied for preventing rigid body motion, so that it relevantly simulates free heating condition of the package. As shown in Figure 11, the entire package is modeled in detail including all components inside.

For the most MEMS sensors during normal operations, the ambient temperature is in steady state, so the transient loading time (t) effect in the constitutive equation is negligible. Therefore, we can use the steady-state incremental linear elastic (ILE) method to take into account the temperature-dependent properties of the fully cured mold compound by accumulating the incremental stresses or strain without considering transient loading effect. The ILE method has even been demonstrated to be in good agreement with full visco-elastic calculations (Silfhout *et al.*, 2005). Thus, ILE method is selected to apply loads as a series of small incremental load steps, so that the model may follow the temperature-dependent path as closely as possible. For the

Figure 10 CHS associated with temperature and verification

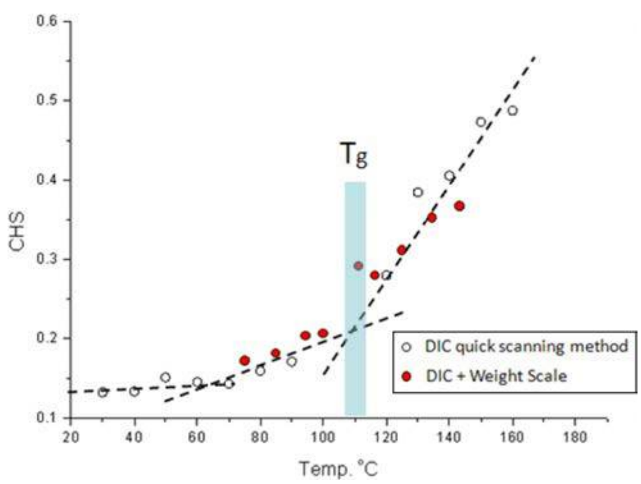


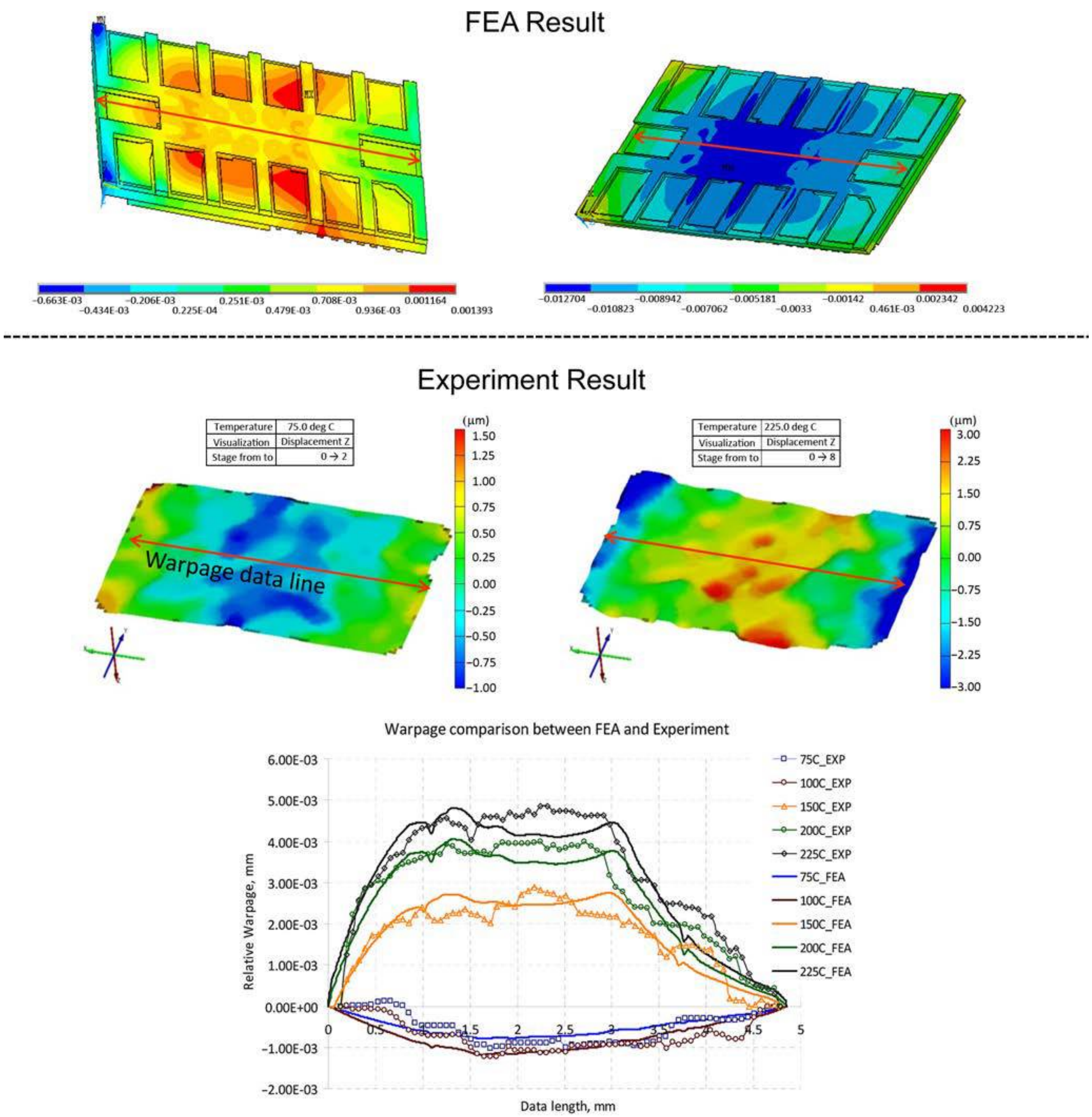
Figure 11 FEA Modeling Detail Model with mold compound encapsulated and decapsulated

validation of FEA model, the warpage simulation and experimental measurement were performed only for temperature loading referenced from 25 and heat up to 225°C.

The simulated Warpage results at 75°C and 225°C were depicted as contour map and compared with experimental result in Figure 12(a). Also, Figure 12(b) shows the warpage line plot comparison, which is along the middle line data on BT core substrate side by definition of warpage. Thus, Figure 12 shows that the simulated warpage result is not only qualitatively, but also quantitatively in good agreement with experimental results. It is also important to remember that this is only thermo-mechanical loading case. By having a confidence from this validation, hygro-material property could be additionally implemented for further analysis.

As mentioned earlier, moisture diffusion and heat transfer are analogous, with parameter relationships such as shown in Table I (Wong *et al.*, 2002). Their constitutive relation on strains becomes a linear combination as illustrated in Figure 13. This superposition method is applied separately to two

Figure 12 FEA validation by thermo-mechanical analysis

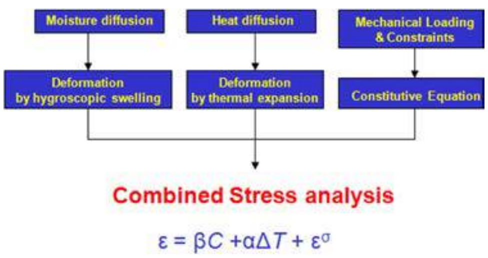


Notes: (a)Warpage contour plots at 75°C and 225°C; (b)Warpage line plot along middle section on BT core substrate side

Table I Analogous parameters between thermal and moisture

Field variable	Thermal temperature (T)	Moisture wetness (w)
Density	ρ	1
Conductivity	K	Dc_{sat}
Specific Heat	Cp	C_{sat}
CTE	α	βC_{sat}

Figure 13 Linear superposition relation for combined stress analysis



temperature ranges because the temperature dependency of CHS as shown in Figure 10.

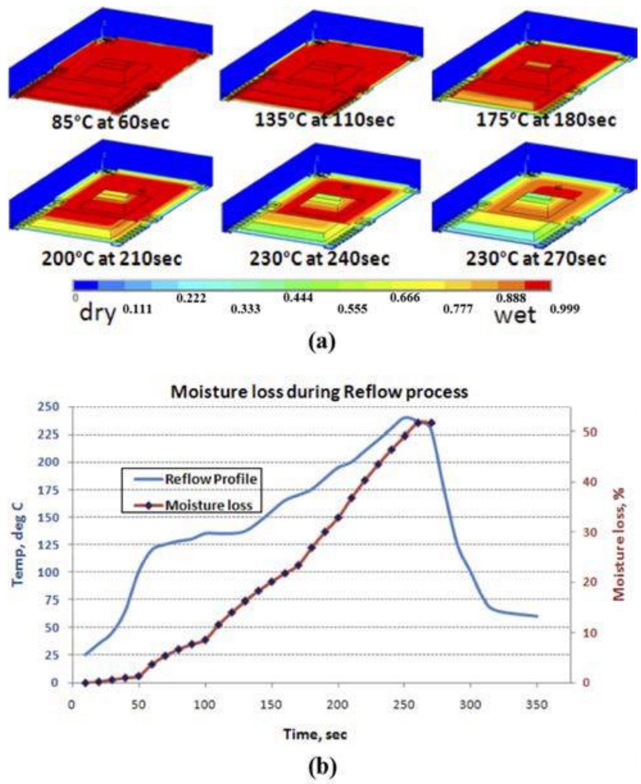
4.2 Transient moisture analysis of mold compound

It is important to know the moisture distribution inside the mold compound during reflow process because the hygro-strain depends on it as well as the amount of moisture inside. Using the experimentally obtained diffusivity, the transient moisture diffusion analysis was performed. In this analysis, the initial boundary condition was given for outer surface, as $w = 0$ (dried), the dried ambient condition at high temperature, while inside the mold compound was given wetness as $w = 0.99$ (wet), the saturated condition after preconditioning. Thus, it is simulating moisture desorption from the overall package during reflow process for approximately 5 minutes. Figure 14 shows the result of transient analysis, (a) contour plot of moisture distribution and (b) average amount of moisture loss during reflow. This moisture distribution is accounted into the hygroscopic stress analysis.

4.3 Integrated warpage and stress analysis

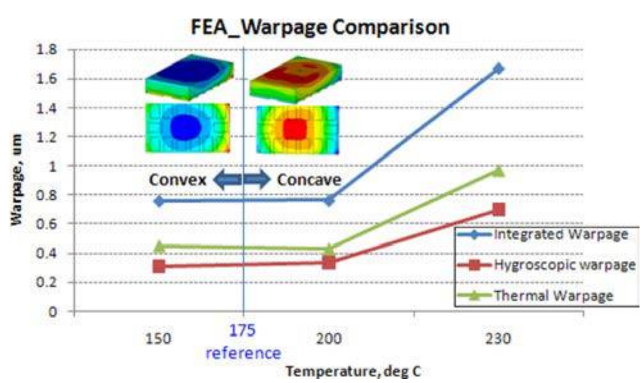
High thermal conductivity was assumed for overall package, which means temperature distribution is uniform during the reflow process. The average moisture contents at different temperatures obtained in the previous section were used in the analysis. Also, assuming the MEMS package to be stress-free at the mold curing temperature, 175°C, the package deformation during the temperature change from 150°C to the reflow temperature, 230°C, was analyzed. Figure 15 shows the warpage comparison for three different analyses that are thermal, hygroscopic and integrated (thermo-hygroscopic) under the same temperature loading. It is observed that the thermo-hygro-mechanical warpage is significantly larger than either the hygroscopic or the thermal warpage. Also, the warpage contour plot shows the package deforms to a convex-up shape away from the BT core side at 150°C, but changes to the opposite, concave shape, at 200°C and 230°C. It is expected because the reference for loading is at 175°C.

Figure 14 Transient moisture diffusion analysis for moisture distribution



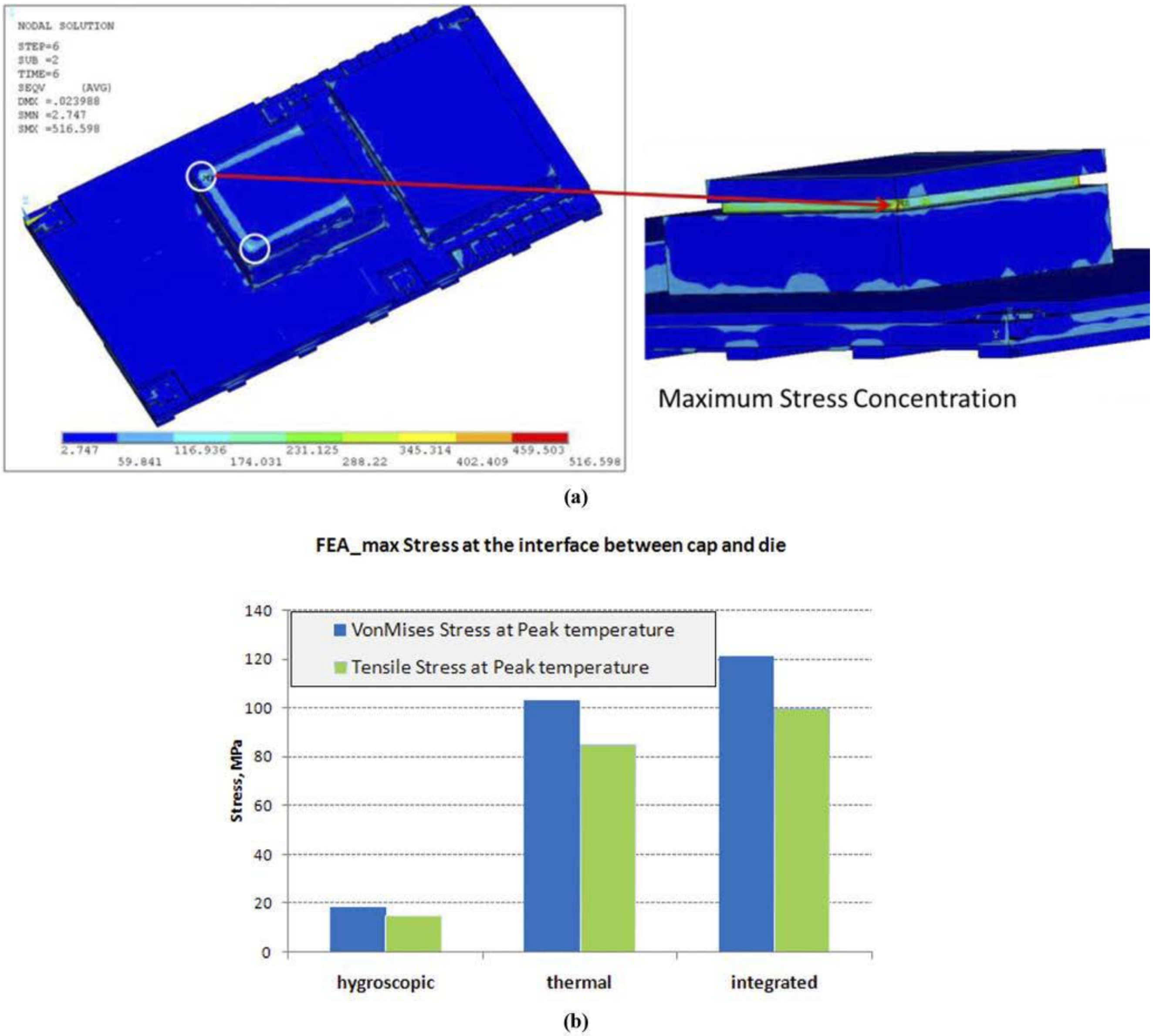
Notes: (a) Transient moisture contour; (b) average moisture loss during reflow

Figure 15 Warpage comparison from 150°C to 230°C



The stress state was also estimated for each analysis inside the MEMS package as shown in Figure 16. Figure 16(a) indicates the stress concentration located at the corner of interface between MEMS die and cap where the sealing glass material is used. Also, Figure 16(b) shows the differences in stress levels for the three different analyses. Obviously, the combined thermo-hygro-mechanical strain mismatch induces higher stress than the others. More specifically, hygroscopic swelling effect in the integrated stress is approximately 20 per cent. It is also noted that the hygroscopic stress is less than the thermal stress. This is due to the difference in T_g effect of mold compound resulting in higher coefficient of thermal

Figure 16 Maximum stresses inside the MEMS package



Notes: (a) Location of maximum stress concentration; (b) stress comparison

expansion (CTE) interaction than CHS mismatch between the components. In addition, the tensile stress is found to be the most dominant stress component. Especially, as expected from the warpage result shown in Figure 15, the tensile stress is dominant above 175°C, while the compressive stress should be dominant below 175°C due to bending moment behavior at the corner of sealing material. The addressed issue regarding this particular location is a structural anomaly (void and porosity) in the sealing glass due to contaminant embedded in the glass during manufacturing (Ghaffarian *et al.*, 2002). Consequently, it would be a concern to hermeticity of MEMS device (Ramesham *et al.*, 1999). Thus, in this issue, the most suspicious failure mode would be crack/delamination at the corner of sealing material due to tensile stress.

5. Conclusion

The hygroscopic material properties of a mold compound used in encapsulation of MEMS devices were measured at various temperatures, and their characteristics are presented. The diffusivity (D) of a mold compound exponentially increases with temperature following the Arrhenius equation. Also, the saturation (C_{sat}) of moisture concentration for this mold compound has a linear relationship with temperature. Thus, D and C_{sat} could be predicted at all temperatures. The CHS at various temperatures were obtained from the proposed experimental method which involves DIC and precision weight scale. The CHS results show temperature dependency trend intersecting at 110°C, which is T_g of this particular mold compound. Then, CHS property was implemented in the FEA to analyze the conjugated effect of hygroscopic and thermo-mechanical behavior of the MEMS package. Using the classical analogy between thermal conduction and moisture diffusion, the transient moisture analysis is performed for a fully saturated specimen showing moisture loss during the reflow process.

Finally, using superposition method, FEA was performed to simulate the MEMS package's deformation behavior during the reflow after fully saturated at 85°C/85 per cent RH. From the FEA results, warpage behavior and stresses state inside the package was investigated. As expected, the thermo-hygro-mechanical deformation yielded the highest warpage and stress than the thermal or hygroscopic strains. Also, the maximum stress occurred at the interface between MEMS die and cap where the sealing glass was used. As the tensile stress is the most dominant stress in this location at 230°C (peak temperature during reflow), the crack/delamination is the most suspicious mode of failure.

The prediction of deformation behavior of the saturated MEMS package during reflow is provided as an effective method for evaluating reliability of plastic encapsulated MEMS devices. This study can also be applied to reliability study on failure mechanism of microelectronics package under constant humid environment and rapid temperature change.

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Further reading

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Corresponding author

Jae B. Kwak can be contacted at: jae.kwak@samsung.com