

Filler Dispersion in Epoxy Mold Compound and Its Effect on the Reliability of Cu/Low-k Devices in Plastic Ball Grid Array Packages

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Abstract

The inorganic filler is an important constituent of epoxy mold compound as it greatly affects critical material properties of the molding compound including CTE and modulus. In this study, the filler distribution in thermally enhanced PBGA packages with different structures and mold compounds were investigated. Optical microscopy inspection found that a region with low filler volume existed near the corner of the die that was opposite to the mold gate. The filler volume reduction was estimated to be 10~20%, depending on the package structure and the type of mold compound. The filler reduction resulted in locally higher-than-nominal CTE in the mold compound. The associated higher thermal strain was confirmed by Moiré interferometry study. Because of the higher strain/stress, most of the failures in the temperature cycling test were observed at the corner with the filler reduction. It was estimated by finite element analysis that the crack driving force at filler reduced corner was 70%~140% higher than that at other die corners with nominal properties.

Key words: Epoxy Mold Compound, Filler, Low-k, Ball Grid Array, Reliability

Introduction

Wire bond ball grid array (WB-BGA) is one of the major package types for semiconductor products. Epoxy mold compound (EMC) is used to encapsulate the die and bond wires in WB-BGA packages. The purpose of the encapsulation is to provide electrical insulation as well as to protect the die and wires from environmental factors such as humidity, dust, physical shock, etc. In order to fulfill all the requirements, EMC is formed as a complex composite material with thermoset resin as the matrix with various additives including inorganic filler, hardener, catalyst, coupling agent, flame retardant, stress relief agent, colorant, and mold release agent. The coefficient of thermal expansion (CTE) of the thermoset resins is in the range of 50–90ppm/°C, while the CTE of the silicon die is around 2.3–2.6ppm/°C. Thermal stress is thus induced by CTE mismatch in the package. To minimize the thermal stress and improve reliability, inorganic fillers, such

as SiO₂ (with a CTE of 0.6ppm/°C), are added into the resin matrix to reduce the CTE of EMC. In the meanwhile, the effective modulus of EMC will also be affected by the fillers. Various models have been developed to predict the mechanical properties of composite materials such as EMC [1-5]. The effective CTE and modulus of composite material are functions of its constituents' properties

$$\begin{aligned}\alpha_C &= f(\alpha_A, \alpha_B, c, \dots) \\ E_C &= f(E_A, E_B, c, \dots)\end{aligned}\quad (1)$$

where α is the CTE, E is the modulus, c is the volume fraction, C , A , B denote the composite material and its constituent A and B. For the mold compound, the volume fraction of the filler is a key parameter since it controls the CTE and modulus when the base epoxy resin and filler population are fixed. The nominal filler volume fraction is

optimized by the EMC manufacturers to balance the request of minimizing CTE mismatch while maintaining good EMC flowability during transfer molding. Ideally, the spatial filler distribution inside the EMC should be uniform with the nominal filler volume fraction to achieve best performance. However, the distribution of the fillers is often disrupted and altered during the transfer molding process when the mold flow is obstructed by structures such as the die and the wires inside the mold cavity. Huang *et al* measured filler distribution in MQFP and PQFP packages and found a 10% difference in filler content across different regions of the package [6]. The resulting difference in CTE was 27~44%. Depending on the design of the package, the non-uniformity in filler content distribution across the package can be severe enough to result in significantly higher thermal stresses in some locations of the package and thus degrade the reliability of the package. The situation becomes even worse with the usage of low-k interlayer dielectrics.

In this work, the impact of filler distribution on package reliability was systematically investigated using WB-BGA packages with low-k devices. Multiple packaging structures and mold compounds were evaluated. Optical microscopy combined with digital image processing was adopted to analyze the filler distribution throughout the package in the molded devices. The mechanical properties change of the EMC with different filler distribution were estimated with theoretical model and confirmed with high-resolution Moiré analysis. The PBGA packages were submitted to air-to-air temperature cycling (AATC) test as well. The correlation between filler distribution and failure from AATC test was studied. In the meantime, the estimated filler content variations were used as the inputs to the finite element model, which was established to assess the impact of filler distribution on thermal stresses and crack driving force in these packages.

Experimental

A 31x31mm thermally enhanced PBGA (TEPBGA) package was selected as the test vehicle. The silicon die in the package has Black Diamond™ (BD) low-k material in back end of the line (BEOL) layers and SiN/SiON as the final passivation. Mold compounds from one of three different suppliers, A, B and C, were used. Major properties of the mold compounds are listed in Table 1. Packages with mold compound A was molded with or without an internal heat spreader (TEPBGA-1 vs. TEPBGA-2) as shown in Figure 1. The other two mold compounds were only applied in TEPBGA-II packages.

Table 1. Properties of mold compounds

EMC	A	B	C
T _g (°C)	150	135	145
Filler Volume (vol%)	79	79	79
CTE (ppm/°C)	<T _g	9	8
	>T _g	49	34
Modulus (GPa)	<T _g	26	23
	>T _g	0.8	0.8

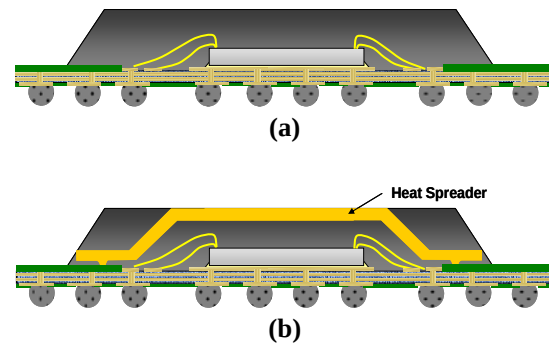


Figure 1. Structure of (a) TEPBGA-I and (b) TEPBGA-II packages

Transfer molding was applied to encapsulate the silicon die. A mold cavity was pressed onto the substrate on which the die and bond wires had been attached. Preheated mold compound was continuously pressured through a sprue (gate), as shown in Figure 2, and flew into the mold until it filled the entire cavity and cured.

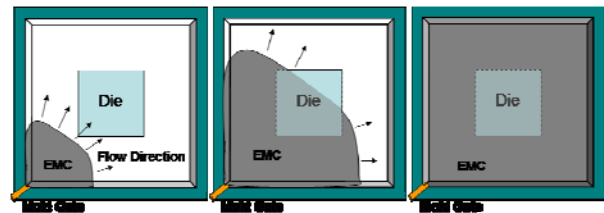


Figure 2. Transfer Molding Process

After the package assembly was completed, two types of samples were prepared for spatial filler distribution study. The first was a thin-slice sample as illustrated in Figure 3. It was prepared by grinding/polishing off the EMC/substrate above and below the die. For filler distribution observation, the sample was illuminated from underneath and the light

that penetrated the thin slide formed an image in the digital camera above. The images acquired in this fashion provided an overview of the filler distribution in a large region that extends to the entire molded cavity in transverse direction of the die. The second type was a cross-section of the original package. The plane of cross-section was along the diagonal line of the die as shown in Figure 4. From this sample, one can examine the filler distribution along the thickness of the die with bright-field microscopy. For later clarification, the corner of the die that is closest to the mold gate is named Corner 1 or C1. The other 3 corners of the die are named C2, C3 and C4 clockwise as indicated in Figure 4.

Scion Image macros were developed for the software to automatically identify the filler particles, calculate the average particle diameter, and obtain the area fraction (AF) of the fillers. Assuming that the area fraction is proportional to the volume fraction, the relative change in volume fraction between different regions in the mold compound can then be calculated.

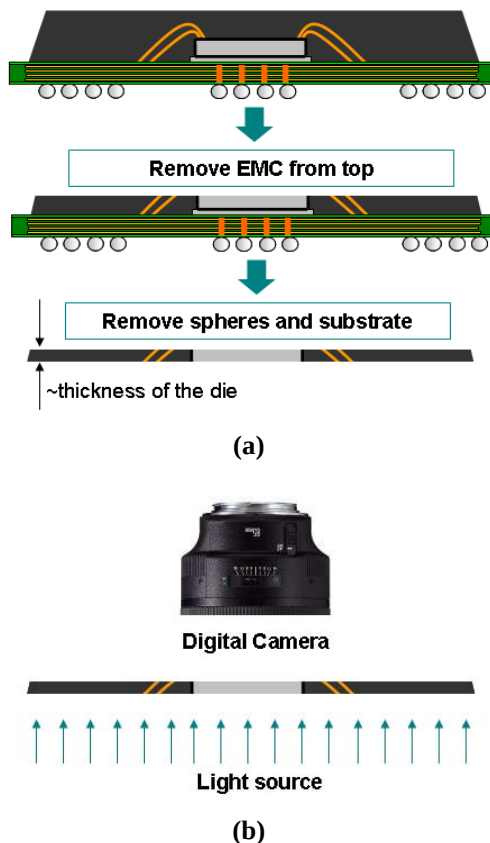


Figure 3. Thin slice sample
(a) Preparation (b) Imaging

Moiré interferometry technique was used to measure the thermo-mechanical behavior of different

regions of the package that had different filler volumes. A 1200 lines/mm grating was applied to the cross-section surface at elevated temperature and then cooled down to room temperature (23°C). Phase-shift technique was applied to ensure sufficient sensitivity to study the local deformation within very small areas in the packages.

The assembled packages were submitted to preconditioning with moisture sensitivity level 3 and Pb-free assembly condition according to IPC/JEDEC J-STD-020B. The packages were then temperature cycled at -55/125°C following JESD22-A104C, condition B. Scanning acoustic microscopy (SAM) was applied at read points to inspect for structural integrity. Packages with defects such as crack or delamination were cross-sectioned using focused ion beam (FIB) and examined with scanning electron microscopy (SEM)

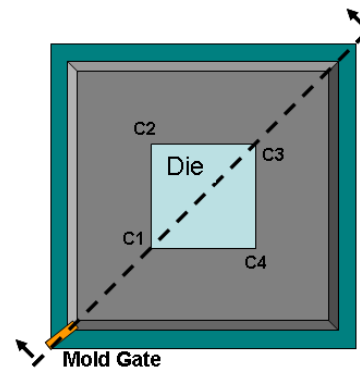


Figure 4. Cross-section sample preparation

Results and Discussion

Filler Distribution Inspection with Thin Slides

The thin slide images of TEPBGA-I and TEPBGA-II packages with mold compound A are shown in Figure 5. The light contrast in the EMC caused by variation of filler content can be clearly seen. Because SiO₂ fillers are nearly transparent and the epoxy matrix is not, regions with higher filler content are brighter than those with lower filler content.

In Figure 5, one can see that the filler distribution in the mold compound was not uniform in either the TEPBGA-I or the TEPBGA-II package. The region close to corner 3 of the die was darker compared to the regions close to corner 1, 2 or 4 of the die, indicating that the former had less filler content than the latter. The difference was more obvious in TEPBGA-II than in TEPBGA-I packages. Particle settling during the molding process may have caused this non-uniform filler distribution. Particle

settling is described as filler particles “sinking” under their own weight [7]. At the beginning of the molding process, the molten EMC was compressed through the gate into the mold cavity with large speed. The fillers were carried away by the epoxy without much time to “settle”. After the EMC passed corner 1 of the die and moved over to the die top, the speed of the flow was reduced due to reduced gap, increased capillary pressure and friction. More and more fillers settled as the molten EMC moved toward the corner 3, resulting in less filler content there compared to corner 1. For TEPBGA-II package, the gap over die top was further reduced compared to TEPBGA-I because of the heat spreader.

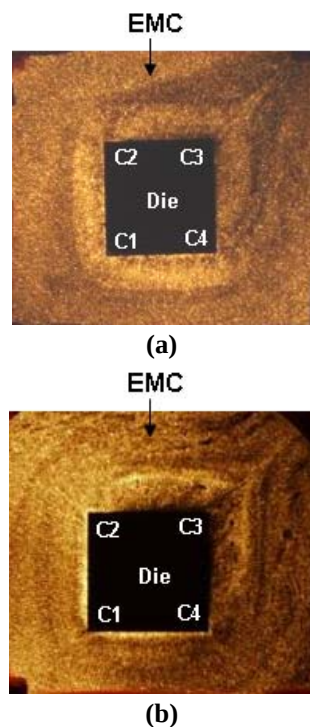


Figure 5. Thin slides image of (a) TEPBGA-I and (b) TEPBGA-II packages with EMC A

The thin slide image of TEPBGA-II package with the three different mold compounds A, B and C are shown in Figure 6. The differences between corner 1 and corner 3 regions were still obvious for all three EMCs. However, the difference among the mold compounds was not very clear. To better quantify the filler content in different locations in the EMC, cross-sectional image analysis was applied.

Filler Distribution Analysis with cross-sections

A cross-section along the diagonal line connecting corner 1 and corner 3 of the die was chosen for the analysis. A typical optical image of such a cross-section is shown in Figure 7. It can be seen that the volume fraction of filler near corner 1 was close to the nominal value which were demonstrated in the region far away from the die. In contrast, the filler content was considerably less in the area near corner 3 and adjacent to the vertical edge of the die.

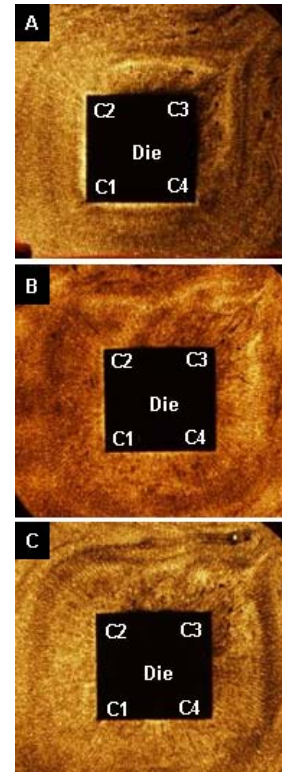


Figure 6. Thin slides image of TEPBGA-II with EMC A, B and C

Regions of $200 \times 200 \mu\text{m}$ adjacent to the vertical edge and below the top surface of the die were used to analyze the filler fraction. Assuming the filler content near corner 1 to be 100% of the nominal value, the relative filler volume fraction near corner 3 was calculated from measurement and reported in Table 2. It can be seen that the maximum filler volume fraction reduction occurred near corner 3 in the package with TEPBGA-II structure and EMC A.

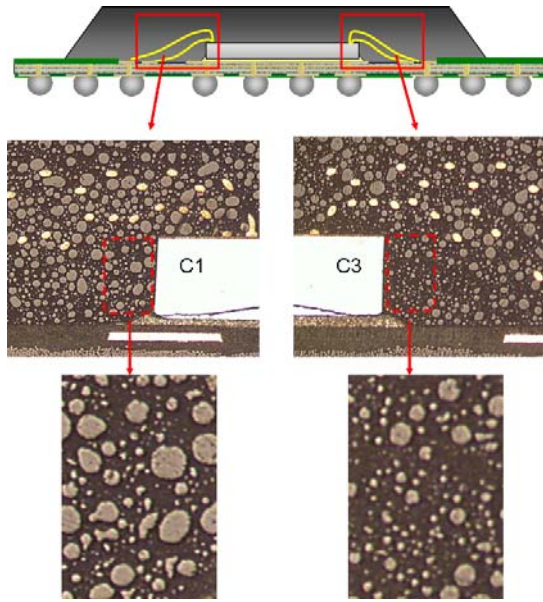


Figure 7. Optical image of typical cross-section of TEPBGA package

Table 2. Filler volume near corner 3

Corner 3 relative filler volume (%)		EMC		
		A	B	C
Package Type	TEPBGA -I	90	x	x
	TEPBGA -II	80	85~90	85~90

Moiré Interferometry Analysis

Moiré interferometry study was performed on TEPBGA-II package with EMC A. The grating was applied at 83°C (stress free temperature) and the analysis was carried out at 23°C, representing a thermal load of -60°C. The areas of interest were the regions near corner 1 and corner 3 of the die.

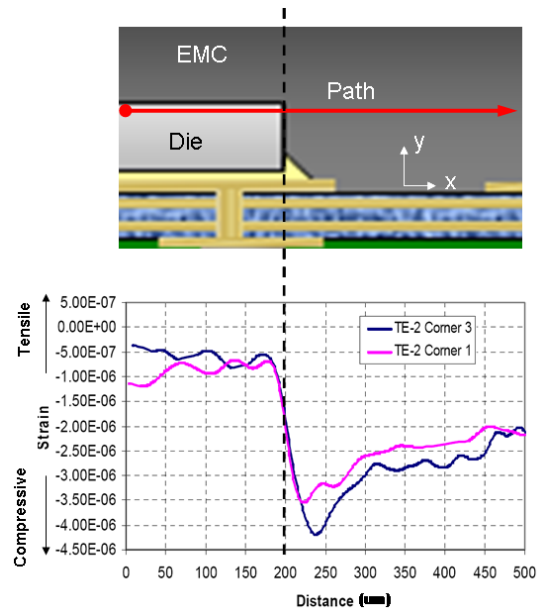


Figure 8. Moiré interferometry analysis of EMC with different filler volume

A path was drawn along the surface of the die and extended into the mold compound, as shown in Figure 8. Strain information was calculated along the path from the phase map obtained by high resolution Moiré. Strain in x direction, ϵ_x , along the defined path is shown in Figure 8. The strain increased sharply toward the compressive direction after the path went from the die into the EMC due to the large CTE of EMC. The peak value of the strain at corner 3 was ~20% larger than that at corner 1, indicating material property difference between these two regions. Corner 3 experienced larger strain which can be associated with larger mechanical stress.

Table 3. Reliability stressing results

Temp cycles when first failure occurred		EMC		
		A	B	C
Package Type	TEPBGA -I	>2000	x	x
	TEPBGA -II	500	>1500	800

Reliability Test Results

Reliability test results are shown in Table 3. Tracking of the failure locations confirmed that nearly all the failures occurred on the bond pads close to corner 3 of the die, regardless of package type and EMC type. No failure was found near

corner 1 of the die. The trend was clear that the region with larger filler reduction has higher possibility to show failure during thermal-mechanical test.

FIB cross-sections of failed samples are shown in Figure 8. Two failure modes were observed. The first one was the delamination at the interface between the EMC and the die top passivation, as shown in Figure 9(a). The delamination propagated along the interface and cracked the wire bond eventually. The second failure mode was the delamination and cracking in the low-k ILD layers, as demonstrated in Figure 9(b). The cracks fractured the Cu lines and opened the vias and caused electrical failure.

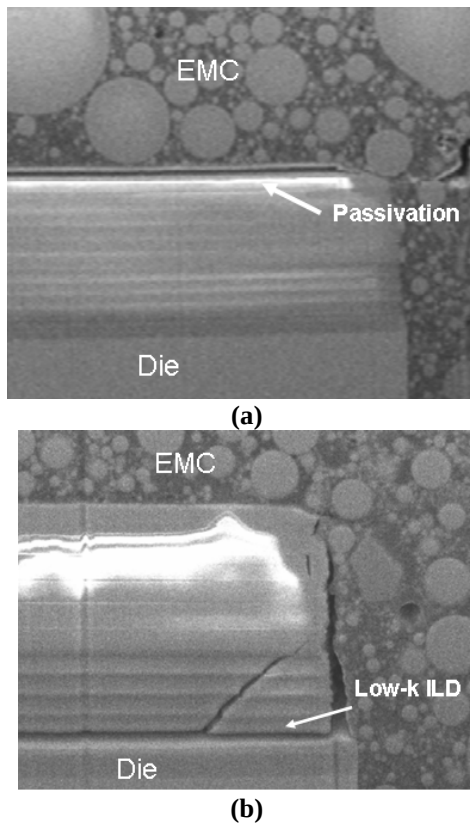


Figure 9. Failure analysis of low-k device after temperature cycling (a) EMC/passivation delamination (b) Low-k ILD cracking

Finite Element Analysis

A 2D finite element model was set up to analyze the stress distribution inside the TEPBGA-II package during temperature cycling. The model represents the diagonal plane that passes through

corner 1 and corner 3 of the die, as shown in Figure 10. One half of the package was simulated based on symmetry. To simulate the filler reduction phenomenon near corner 3, the material properties of the elements near one corner of the die was adjusted from the nominal values based on the filler volume listed in Table 2 and the data from EMC suppliers. The adjusted properties of the EMC are listed in Table 4.

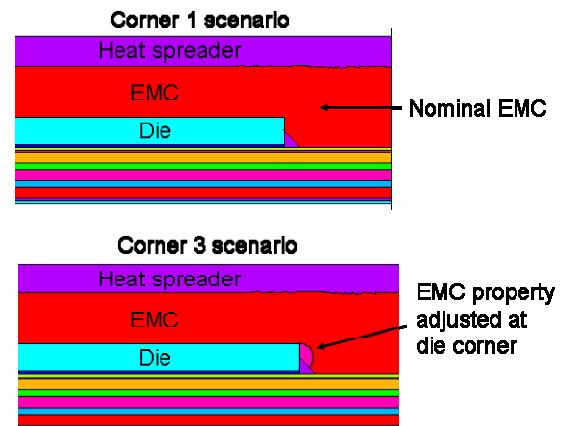


Figure 10. Finite element model of TEPBGA-II package

Table 4. Properties of EMC at corner 3

EMC		A	B	C
Filler Volume at corner 3 (vol%)		63	69	69
CTE (ppm/°C)	<T _g	18	13	15
	>T _g	98	55	58
Modulus (GPa)	<T _g	13	18	18
	>T _g	0.4	0.6	0.5

Since both the failure modes at corner 3 are interfacial delamination, the energy release rate (ERR) would be a good parameter to describe the driving force for the failure. A sub-model was developed focusing on the detailed structure near the surface of the die as shown in Figure 11. Pre-cracks were inserted into the model at the expected failure interface as defects for energy release rate study. The thermal load used in the study was from 175°C which is the molding temperature to -55°C which is the lower end of the temperature profile of temperature cycling.

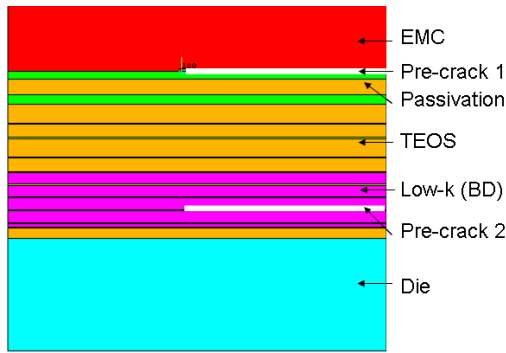


Figure 11. Sub-model for energy release rate calculation

Analysis result showed that shear stress was the dominant stress form at both failure locations which lead to the formation of type II cracks. Figure 12 and 13 compared energy release rate for both interfaces with respect to EMC type and die corner scenario. The energy release rate in corner 3 scenario is 70%~140% higher than that in corner 1 scenario regardless of the location of the interface and the EMC type. This result agreed well with the findings from the reliability study. The difference in ERR induced by EMC type, on the other hand, is only 3%~5%. The outcome of the analysis suggests that, for a mold compound, the capability of maintaining its nominal filler volume throughout the entire package during the mold process is at least as important as the actual properties themselves. For best thermal-mechanical performance, minimum filler volume reduction should be maintained inside the mold compound.

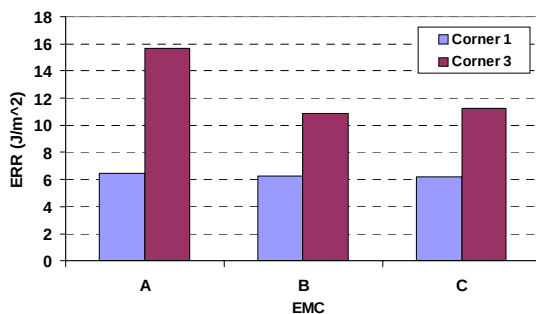


Figure 12. Energy release rate for delamination at EMC/passivation interface

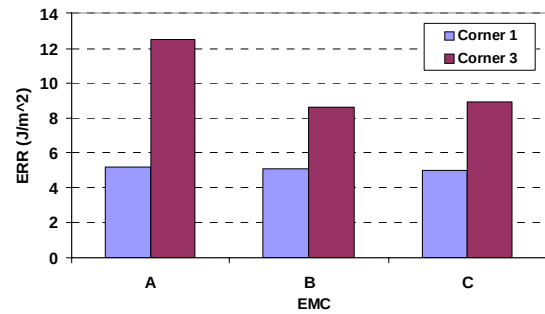


Figure 13. Energy release rate for delamination in low-k ILD layers

Conclusions

In this work, the filler distribution in TEPBGA packages with different package structures and mold compounds were studied. Optical microscopy inspection found that a region with low filler volume existed near the corner of the die that was opposite to the mold gate. The filler volume reduction was estimated to be 10~20%, depending on the package structure and the type of mold compound. The variation in filler volume will induce mechanical property change of the EMC. High resolution Moiré study confirmed that higher mechanical strain/stress can be expected in the EMC when the filler volume was reduced. The temperature cycling test also showed that most of the failure were observed at the corner with the reduced filler content.. It was estimated by FEM analysis that the crack driving force at corner 3 was 70%~140% higher than that at other die corners with nominal EMC properties. The results suggest that the localized filler non-uniformity is a significant degrading factor on BGA package reliability and must be minimized as much as possible.

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