Control of Package Warpage by Package Substrate Design for Low Profile Package-on-Package Structure

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Abstract:

In recent years, with increasing demand for high-density assembly in mobile electronics products, a package-on-package (PoP) structure has been standardized. The demand for lowering the PoP profile is getting stronger as consumers demand thinner mobile devices. To assemble a low profile PoP and mount it on a mother board, it is necessary to have a precise warpage control of PoP components, including its bottom package. It is expected that a flip-chip chip-scale-package (FCCSP) with thin mold cap will be used as the bottom package of the PoP in the next 2-3 years. In order to control the package warpage, it is necessary to optimize a large number of parameters related to the package substrate, silicon die and mold compound. Among them, equivalent coefficient of thermal expansion (CTE) of the package substrate is one of the most important factors.

In this paper, control of the package warpage was studied by focusing on the glass-cloth content ratio in the package substrate. Glass-cloth has the lowest CTE among the constituent materials of the substrate, so it contributes to reduce the equivalent CTE of the substrate. To maximize the glass-cloth content, a substrate with a thick core and thin build-up structure was prepared, and the package with thin mold cap was subsequently formed. Compared with a similar package with a conventional substrate structure, its warpage, measured experimentally, was about 20% smaller. Consequently, it was concluded that the glass-cloth content ratio is a key factor to control package warpage behavior in the PoP assembly process.

Keywords: package warpage, equivalent CTE of a package substrate, glass-cloth content ratio

Introduction

A general package-on-package (PoP) structure is described in Figure 1. PoP consists of the top package (memory) and the bottom package (processor). These are fabricated separately by their own processes and then joined together, so high assembly yields can be obtained. Due to this reason, PoP structure has become the preferred technology for small form factor for applications such as smart phones and netbooks [1], [2]. In recent years, there is a trend to use a flip-chip chip-scale-package with fully molded structure, also called a through mold via (TMV), as the bottom package in PoP [3], [4].

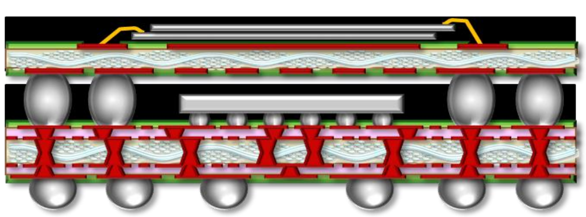

Fig.1 Generic PoP configuration

Smart phones and netbooks require a high density assembly in limited space. Additionally, there is a strong demand for thinner mobile devices, so limitations on the total height of the components are severe. PoP structure is optimum from high density assembly point of view, but it is one of the thickest components in smartphones, so thinner profile PoP structure is strongly demanded.

However, to decrease PoP height, there are some challenges, such as fine pitch solder ball, thin mold, stacking up of thin dies, etc. One of the most important challenges is to control package warpage. Package warpage brings on assembly faults such as solder short and open, so package warpage specification is defined depending on solder volume and ball pitch. In general, package warpage develops because of the CTE mismatch between silicon die and organic substrate. A low profile package shows bigger warpage than a thick one. Generally, shrinkage of mold cap aids in lowering the package warpage. However, in a low profile package, this warpage-lowering effect is small because the thin mold cap does not generate enough force during shrinkage, as Figure 2 shows. Therefore, to control low profile package warpage, not only mold property but also substrate structure is needed to be optimized.

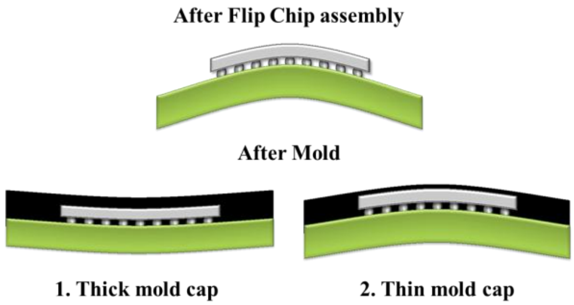

Fig.2 Package warpage behavior with thick or thin mold cap

Package warpage is caused by the CTE mismatch between Silicon die and substrate, so minimizing the CTE mismatch has strong effect on decreasing package warpage. To reduce equivalent coefficient of thermal expansion (CTE) of substrate, glass-cloth that has the lowest CTE in substrate can be a key factor.

In this paper, in order to realize a low profile package with small warpage, focus was given on the glass-cloth content ratio in substrate. Several different substrates were prepared, and then the package warpage and equivalent CTE of each ones were evaluated. Also, finite element analysis was carried out to extrapolate the experimental results. From this study, it was clear that package warpage and equivalent CTE of substrate correlated strongly with glass-cloth content ratio in substrate. The substrate with a thick core and thin build-up structure showed a small package warpage value, because it had the biggest glass-content ratio. Finally, it was concluded that to decrease low profile package warpage, thick core and thin build-up structure substrate was a suitable structure.

Hypothesis

Minimizing the CTE mismatch between Silicon die and substrate will be the most effective method to decrease package warpage. Silicon die mainly consists of homogeneous material, that is silicon, and its CTE is known as 3.2ppm [5]. On the other hand, substrate consists of several materials, so its equivalent CTE depends on the content ratios of each constituent material. Mechanical properties of representative materials in a substrate are shown in Table 1.

Table 1 Mechanical properties of representative materials in a substrate

at 25degC

Material	CTE [ppm]	Young's modulus [GPa]
Glass-cloth	2.8	86
Copper	17	100
Epoxy resin	over 40	5

From this table, it is clear that glass-cloth has the lowest CTE in substrate. The glass-cloth mainly consists of silicon dioxide (SiO2), and the CTE of SiO2 is 0.5ppm, so its property shows low CTE and high modulus. Therefore, the equivalent CTE of substrate, that has high glass-cloth content ratio, is predicted to show low value. The value of glass-cloth content ratio in substrate is calculated by equation (1).

$$A = \frac{\sum_{n=1}^{i} \left(m_i \div d \right)}{T} \tag{1}$$

A: Glass-cloth content ratio in substrate
i : The number of glass-cloth in substrate
m_i: Nominal weight of glass-cloth [g/m2]
d: Density of glass-cloth [g/m3]
T: Substrate height [m]

The nominal weight of glass-cloth is provided by IPC-4412A [6], the density of glass-cloth is 2.54 x 10^6 [g/m3]. Representative glass-cloth's fabric styles are shown in Table 2, which are excerpts of IPC-4412A. In this paper, the substrate thickness is defined as the distance between each side of solder resist surface of substrate.

Table 2 Representative glass-cloth's fabric styles

Style (GC#)	Fabric Count Warp x Fill (per cm)	Thickness (mm) (Reference Only)	Nominal Weight (g/m2)
1017	37.4 x 37.4	0.014	12.3
1027	29.5 x 29.5	0.019	19.9
1037	27.6 x 28.7	0.028	23.0
1078	21.3 x 21.3	0.043	47.8
1280	23.6 x 23.6	0.056	52.9
2116	23.6 x 22.8	0.094	103.8

To study how to maximize glass-cloth content ratio in substrate, the conventional substrate configuration was confirmed (Table 3). In this table, GC# means the fabric style of glass-cloth, its thickness, and weight. They can be also referred from IPC-4412A (Table 2).

Table 3 Conventional substrate configuration and its glass-cloth content ratio

Layer	Thickness [um]	GC#	GC weight [g/m^2]	GC ratio
SR	15			
L1 Cu	15			
1-2	35	#1027	19.9	10.9%
L2 Cu	15			
2-3	35	#1027	19.9	10.9%
L3 Cu	15			
3-4 (Core)	100	#2116	103.8	56.6%
L4 Cu	15			
4-5	35	#1027	19.9	10.9%
L5 Cu	15			
5-6	35	#1027	19.9	10.9%
L6 Cu	15			
SR	15			

From this table, it is clear that the glass-cloth in core layer dominates 56.6% of the total glass-cloth content. Therefore, increasing the thickness of the core layer is important to maximize the overall glass-cloth content ratio. Conventional substrate uses Prepreg, which includes thin and light glass-cloth, as insulator. However, from the above observation, it was found that the glass-cloth in Prepreg is not dominant for its content ratio in whole substrate. In the following study, we tried to maximize glass-cloth content ratio by focusing on the core layer thickness.

Experimental method

To evaluate package warpage, test chips, several substrates, and mold compound are prepared. The test chip design is shown in Figure 3. The test chip has 3,844 solder (Sn3.5Ag) bumps at 150um pitch, the size of the chip is 10.2mm x 10.2mm, and the thickness is 0.10mm.

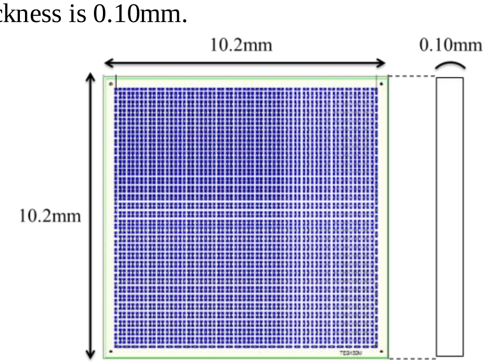

Fig.3 Test chip structure

The test vehicle package configuration is shown in Figure 4. The test chip and substrate are joined with Pb-free solder bumps that are fabricated on the substrate. The substrate thickness is fixed at 0.34mm regardless of each substrate structures to avoid the influence of form factor on the package warpage. The mold thickness, from solder resist surface to mold surface, is 0.20mm. The test vehicle package was molded by using transfer mold method.

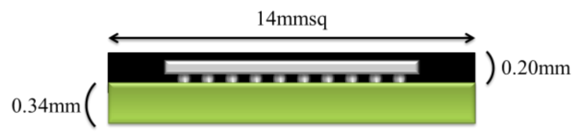

Fig.4 Test vehicle package structure

3 types of substrates are prepared to study the influence of glass-cloth content ratio on package warpage. Each substrate's structures are shown in Table 4. The layer structure of #2 is very similar to a conventional substrate. To study the effect of low glass-cloth content ratio, #1 was prepared. In this case, build up films with no glass-cloth were used as insulating layers. #3, which has a thick core and thin build-up structure, has the highest glass-cloth content ratio.

Table 4 Substrate structures for package warpage evaluation

		#1		#2		#3	
		Thickness [um]	GC#	Thickness [um]	GC#	Thickness [um]	GC#
Layer structure	SR	15		15		15	
	L1 Cu	15		15		15	
	1-2	28.5		28.5	#1017	22	
	L2 Cu	15		15		18	
	2-3	28.5		28.5	#1017		
	L3 Cu	18		18			
	3-4 (Core)	100	#2116	100	#2116	200	#2116 2ply
	L4 Cu	18		18			
	4-5	28.5		28.5	#1017		
	L5 Cu	15		15		18	
	5-6	28.5		28.5	#1017	22	
	L6 Cu	15		15		15	
	SR	15		15		15	
Glass-cloth content ratio		12.1%		17.7%		24.0%	

The experimental approach is noted as below. At first, the equivalent CTE of each substrate was measured by using thermomechanical analysis (TMA) method. Subsequently, packages were assembled with the substrates. At last, the package warpage of each configuration was measured by using Shadow Moiré method. The measurements were taken on the bottom side of the package without solder balls. The direction of the warpage (positive or negative) is defined as shown in Figure 5. The positive direction is cry shape, the negative one is smile shape.

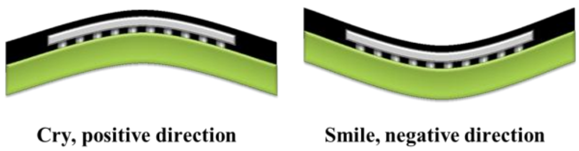

Fig.5 Definition of package warpage sign

Prediction by finite element method (FEM)

In advance to experimental trial, package warpage was predicted by using FEM. Simulation model is shown in Figure 6. Mechanical properties of materials corresponding to each element of this model are shown in Table 5. Furthermore, the values of properties are referred from the catalogues of material suppliers.

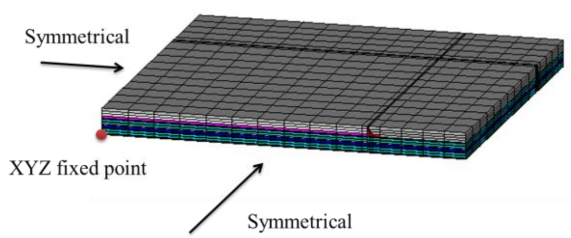

Fig.6 Overview of simulation model

Table 5 Mechanical properties

Material	Young's modulus [GPa]		CTE [ppm]	
	25degC	260degC	α1	α2
Core	32	17	5	2
Prepreg	22	10	7.8	7.8
Build-up film	7.5	0.3	23	78
Copper	112	76	18	18
Silicon	166	166	3.2	3.2
Solder Resist	6.3	0.15	60	124
Solder	50	0.001	22	-
Under fill	11.7	0.3	25	80
Mold compounds	12	0.3	21	70

The model was created as quarter size of test vehicle package, and symmetrical boundary condition was applied to two inner surfaces. The point located in center of bottom surface of package is fixed for all axes (XYZ). Only elastic deformation was considered. All elements of this model are solid shell type. ANSYS 13.0 was used in this study. The final deformation of package was analyzed at 25degC and 260degC. The results of simulated package warpage are shown in Figure 7.

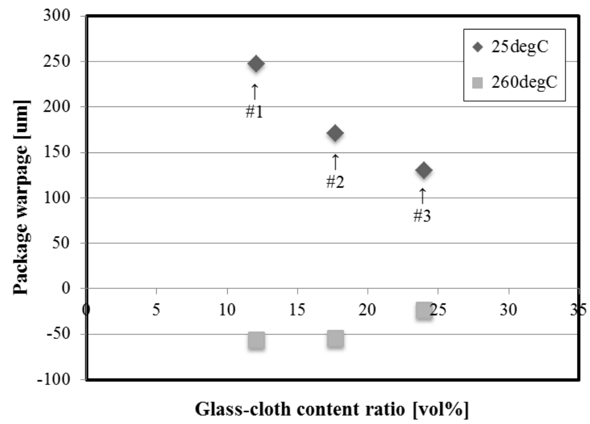

Fig.7 Simulated package warpage results

From these results, it was found that glass-cloth content ratio in substrate correlates strongly with package warpage. Especially, the correlation is stronger in room temperature than in high temperature.

Measurement of equivalent CTE of a substrate

The substrates in Table 4 were fabricated, and the equivalent CTEs of each ones are measured. The measurement results are shown in Figure 8.

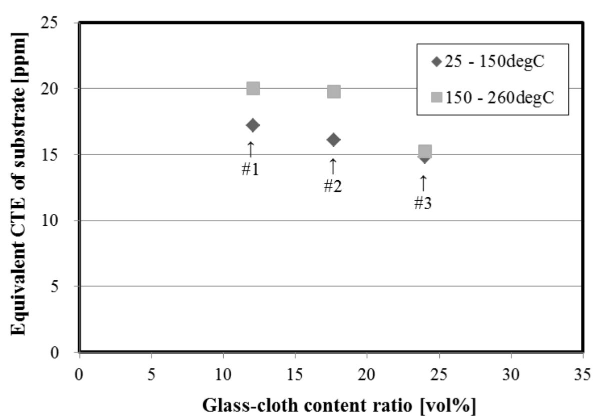

Fig.8 Measurement results of equivalent CTE of substrate

The method of measurement sample preparation is noted as below. The measurement sample was cut from substrate to 5 x 30mm size. Regarding measurement conditions, the load is 0.1N with tensile mode, the temperature range is 25 – 300degC, and the rate of temperature rise is 10degC/min. And then, CTE is calculated from expansion value divided by original sample length in 2 temperature ranges, 25 - 150degC, and 150 - 260degC.

The correlation between glass-cloth content ratio and equivalent CTE of substrate is strong in low temperature range (25 - 150degC), and weak in high temperature range (150 - 260degC). The simulation results and TMA measurement results are well linked. It was found that equivalent CTE of substrate strongly contributes to decrease package warpage.

Measurement of package warpage

The test vehicle packages including each substrate in Table 4 were fabricated. The actual cross section image is shown in Figure 9. Top surface of package is covered with about 50um mold compound, and the gap between Silicon die and substrate is filled by under fill material.

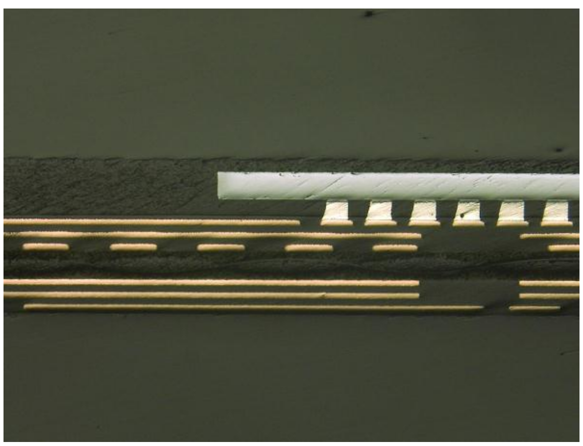

Fig.9 Cross section image of actual test vehicle package

The fabrication process is noted as below. The substrate was fabricated as 47.5mm x 60.5mm frame, and 6 test chips were mounted on substrate by using C4 assembly method. Then, under fill material was injected to the space between silicon die and substrate by capillary under filling method, and it was cured in oven at 150degC. It was molded by using transfer mold method, and was cured in oven at 175degC, then, was singulated to individual packages by mechanical dicing saw.

The measurement result of package warpage of #2 is shown in Figure 10. The package warpage attributes in temperature change had no difference between each 3 substrates.

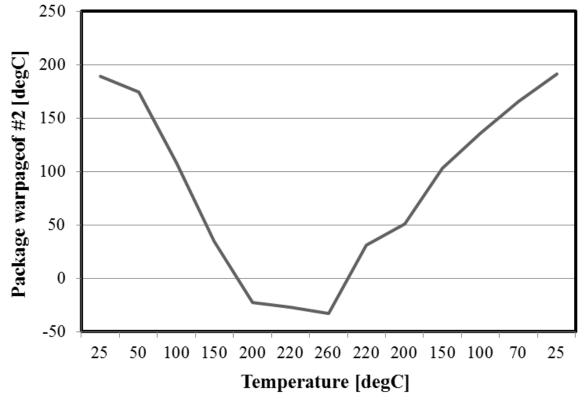

Fig.10 Package warpage attribute in temperature change

From this result, it was found that the package warpage in room temperature is 4 times bigger than in high temperature. It means that, the shrinkage of substrate from reflow temperature mainly effects on package warpage.

And then, the measurement results of each package warpage and comparison of measured / simulated values are shown in Figure 11. In this figure, actual data are noted as the range from Max to Min warpage value.

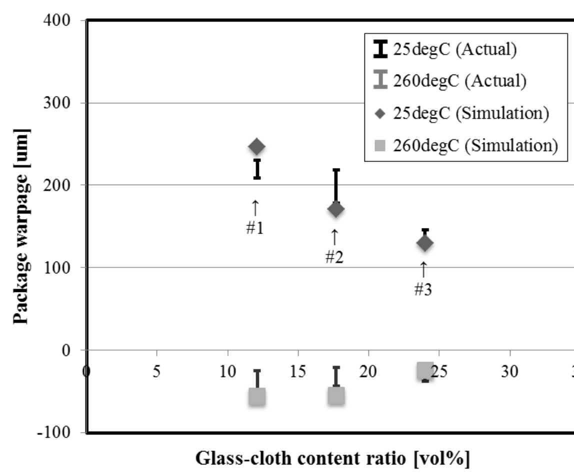

Fig.11 Comparison of measured and simulated package warpage results

From these results and comparison, it was found that glass-cloth content ratio in substrate correlates strongly with package warpage, similar to the simulation results. Especially, #3, which has the highest glass-cloth content ratio, shows more than 20% lower warpage compared to conventional ones (#1, #2).

Discussion

Following 3 key parameters were focused on this study.

1. Glass-cloth content ratio in a substrate
2. Equivalent CTE of a substrate
3. Package warpage

In TMA measurement results, glass-cloth content ratio shows strong contribution to equivalent CTE, because glass-cloth has the lowest CTE among all materials in a substrate. In simulation and package warpage measurement results, glass-cloth content ratio shows strong contribution to decrease package warpage. These facts mean that the above key parameters have clear relationship, and maximizing glass-cloth content ratio is a very effective substrate design strategy to decrease low profile package warpage.

Conclusions

A comprehensive study in this paper shows that high glass-cloth content ratio is an effective solution for decreasing a package warpage. In the current trend of lowering package height, it is difficult to put enough glass-cloth in substrate with conventional design. Therefore, a substrate design that has thick core (rich glass-cloth content) and thin build-up layer is a suitable method to maximize glass-cloth content ratio. In future, more precise package warpage control in PoP assembly process will be needed for next generation mobile products that require ultra-thin package and fine pitch ball connection. We will further study ultra-low CTE substrate focusing on Cu density and glass-cloth materials based on the substrate design that this paper suggested.

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