Accurate Predictions of Flip Chip BGA Warpage

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Abstract

Organic flip chip BGA has been quickly adopted as the mainstream package solution for high speed, high density and high power ASIC and PLD. For these applications, both die and package dimensions are generally large. It is common to see dies over 25 mm and packages of 40 mm or larger. Therefore, warpage is a big challenge. A three-dimensional finite element model was developed to predict the warpage. The model includes substrate, underfill, die, thermal interface material (TIM), heat spreader, stiffener and adhesives. The model has consistently shown excellent accuracy. The average prediction error for a number of packages was less than 10%. The modeling techniques are presented in details in the paper. Using the model, various factors, such as materials and structures of heat spreader, die size and package size, and thermal interface materials were studied.

Introduction

There have been many publications on organic flip chip BGAs in the last few years. Board-level solder joint reliability was studied [1-2]. Many papers were focused on interfacial reliability such as underfill delamination or die crack [3-7]. Saito et al have done an extensive investigation covering five failure modes, which were die crack, underfill delamination, solder bump failure, substrate crack and board-level solder joint failure [8]. Compared to reliability studies, however, little has been published addressing the warpage issue of these packages. In general these packages are large with large dies. For example, a 40-mm package with dies of 25-mm is not uncommon. Due to the mismatch of coefficients of thermal expansion (CTE) of die and substrate, warpage of such packages can easily go over the JEDEC limit of 0.20 mm (8 mils) maximum and reach over 0.25 mm (10 mils). An illustration of a flip chip BGA is shown in Figure 1. For simplicity, the lid and stiffener together is alternatively worded as heat spreader since comparison between one-piece lid and two-piece lid was not included in the paper.

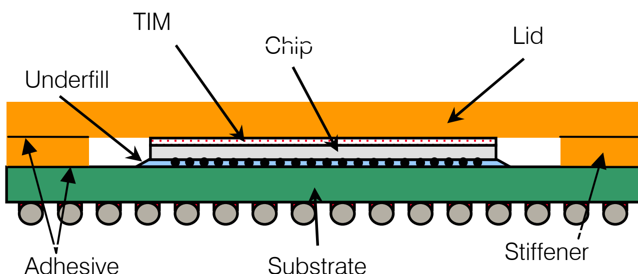

Figure 1. A Schematic of a Flip Chip BGA

Finite element model was used for efficient evaluations. The model was a three-dimensional model which reflected the actual package dimensions including substrate, underfill, die, TIM, heat spreader and adhesives. The model has shown excellent correlations with the actual measured data.

An accurate model was the key to address the warpage issue successfully. Virtual design of experiments were conducted first to screen materials, provide dimensional or structural directions and obtain the optimum parameter settings before actual experiments and implementation were committed. Without it, one would have required exhaustive time-consuming and costly trial-and-error runs and likely still have gotten nowhere. With the model, the following factors were studied to understand their effects on warpage: materials and structures of heat spreader, die size and package size, and TIM.

Finite Element Modeling

The flip chip substrate is a build-up type such as 2-2-2 or 3-2-3, see Figure 2. The core material is bismaleimide triazine (BT) and the dielectric material for the build-up is typically Ajinomoto ABF, which has a much higher CTE than BT. However, it was found not necessary to model the substrate exactly as shown in Figure 2. Instead, it was considered as a homogenous mixture of the component materials. The effective CTE was computed using Equation (1), where α_i and E_i are the CTE and Young's modulus values of the various materials and V_i is the volume fraction of the respective materials [9]. The model is much simpler without losing accuracy.

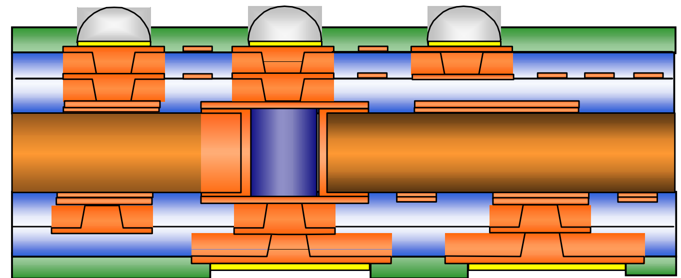

Figure 2. A Schematic of 2-2-2 BU Substrate

$$CTE = \sum(\alpha_i V_i E_i) / \sum(V_i E_i) \qquad (1)$$

ANSYS® [10] was used for finite element analysis. Due to symmetry of the package, only one-quarter of the package needed to be modeled. The model used eight-node 3-D brick elements. A model is shown in Figure 3. For a 35-mm

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package with die size about 27 mm, the number of elements and nodes were approximately 16000 and 20000 respectively.

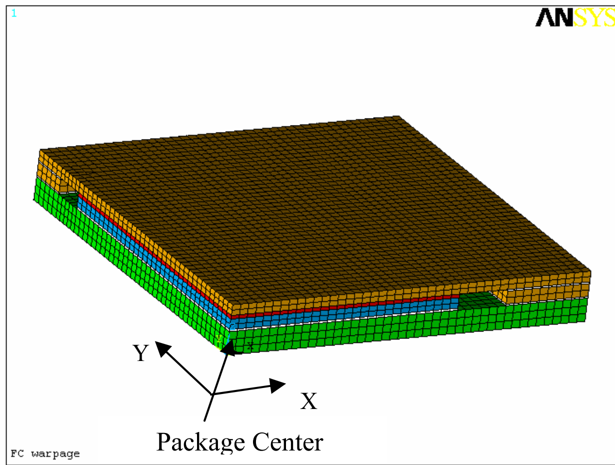

Figure 3. FE Model of Flip Chip BGA

The symmetry boundary conditions were applied to the surfaces at X = 0 and Y = 0. The node at the origin (X=0, Y =0 and Z=0) was fixed in order to prevent free rigid body motion. The curing temperature of underfills was used as the reference temperature which is the stress-free temperature. It is generally 150 ^{o}C. Since it is higher than the glass transition temperature, T_g, of most underfills and adhesives, it is important to present the properties of underfill and adhesive correctly to the model. The Young's modulus and CTE of these materials vary greatly with temperature and Tg.

To verify the model's accuracy, twenty flip chip BGA packages were measured. These packages included three heat spread materials, four heat spreader structures, four underfills and three adhesives. The package size varied from 27 mm to 40 mm. The die size varied from 16 mm to 28 mm. The correlations were excellent as shown in Figure 4. The average prediction error is less than 7%. All the data points are located very closely to the 45 degree line which would represent a perfect match.

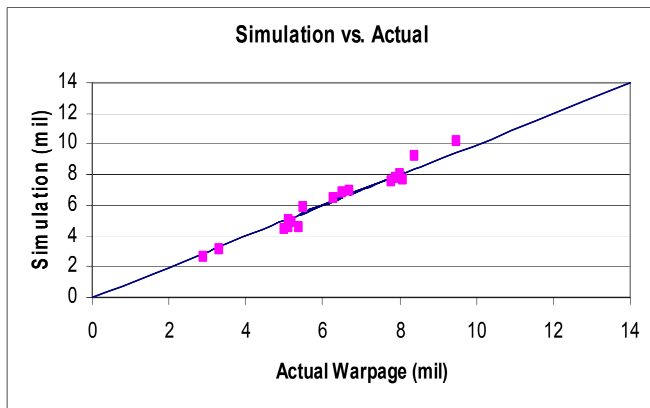

Figure 4. Correlation between Predictions and Measurements

Flip Chip BGA Warpage

CTE mismatch between die and substrate is the major cause of flip chip BGA warpage. While the CTE of silicon die is about 3 PPM, the CTE of the organic substrate is about 17 PPM. Figure 5 is a schematic description of the major manufacturing steps for a flip chip BGA, specifically focusing on the thermo-mechanical deformation experienced by the package. After flip chip bonding and underfill curing, the substrate contracts more than the die and bends into a convex shape causing a "frowning face" warpage. After the heat spreader attachment, the warpage is reduced because the heat spreader tends to pull back the substrate from bending downwards. The flatness of the final package depends on many factors including material sets and structures. The model was used to study the effects of these factors. Some of the results are presented below.

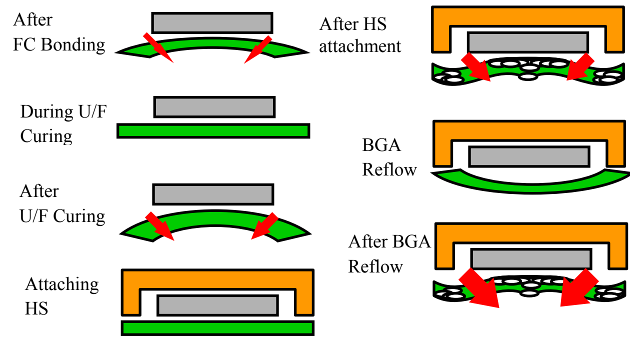

Figure 5. Flip Chip BGA Warpage

Heat Spreader Properties

As mentioned before, in addition to enhancing thermal performance, heat spreader also plays an important role in reducing warpage. The mostly used materials for heat spreader are copper, aluminum and alloys such as AlSiC. Figure 6 illustrates the effect of the CTE of heat spreaders. The minus sign of the warpage values indicates a "frowning face" warpage. It is obvious that higher CTE is better.

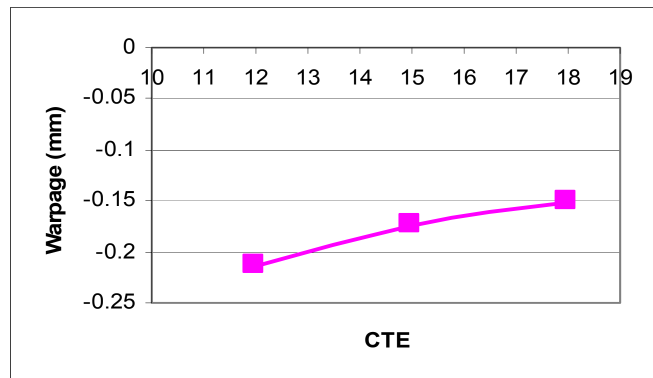

Figure 6. Effect of the CTE of Heat Spreader

Figure 7 shows the effect of the Young's modulus of heat spreaders. The trend is higher Young's modulus, less warpage.

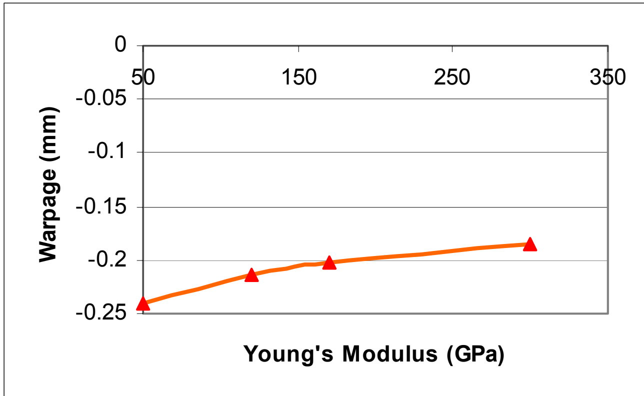

Figure 7. Effect of the Young's Modulus of Heat Spreader

Heat Spreader Structure

Two structures were compared. One is a 4-sided heat spreader (Figure 8) and the other is a 4-corner-post heat spreader (Figure 9).

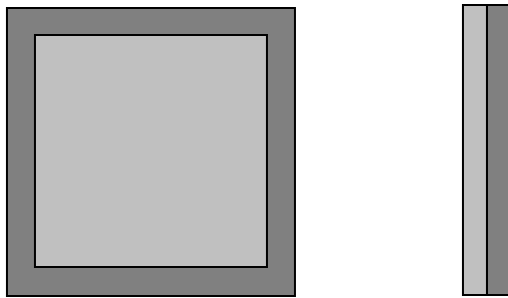

Figure 8. 4-sided Heat Spreader

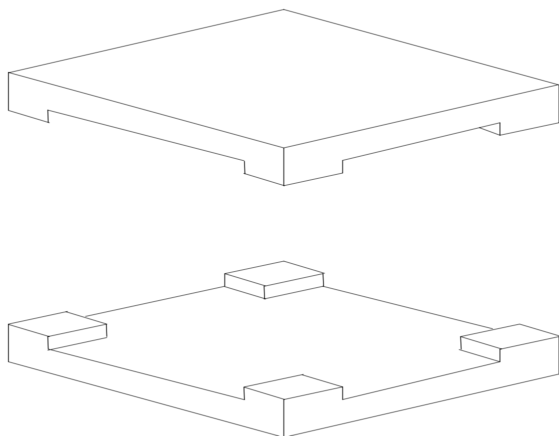

Figure 9. 4-Corner-Post Heat Spreader

The 4-sided heat spreader is more effective in reducing warpage than the 4-corner-post heat spreader. For the same die, using a 4-corner-post heat spreader, a 27-mm flip chip BGA had warpage of 7.8 mils; while a 33-mm package had warapag of 6.7 mils using a 4-sided heat spreader. It is not surprising at all. Mechanically speaking, the effectiveness of a heat spreader in reducing warpage depends on the size of the contacting area between the heat spreader and the substrate. The more contacting area the better.

Die Size

The effect of die size is shown in Figure 10. The package size was kept constant at 33 mm. The larger dies will cause more warpage as expected.

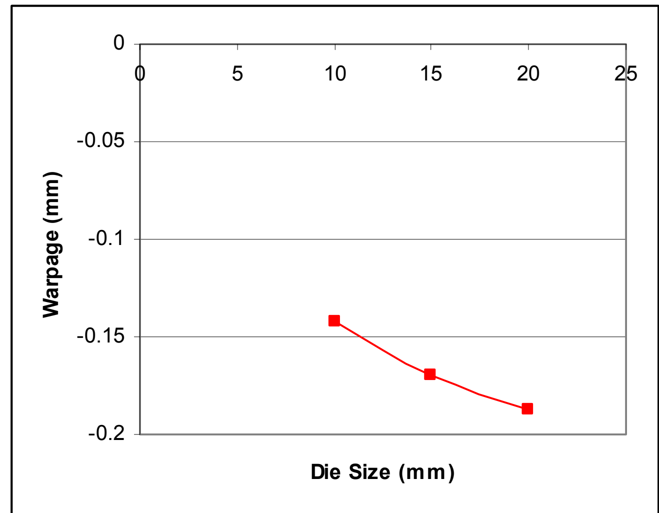

Figure 10. Effect of Die Size

The effect of die thickness was also studied. Thicker die would reduce warpage. The results are shown in Figure 11. Compared to a 0.48-mm thick die, the warpage of the package with a 0.6-mm thick die is 15% less.

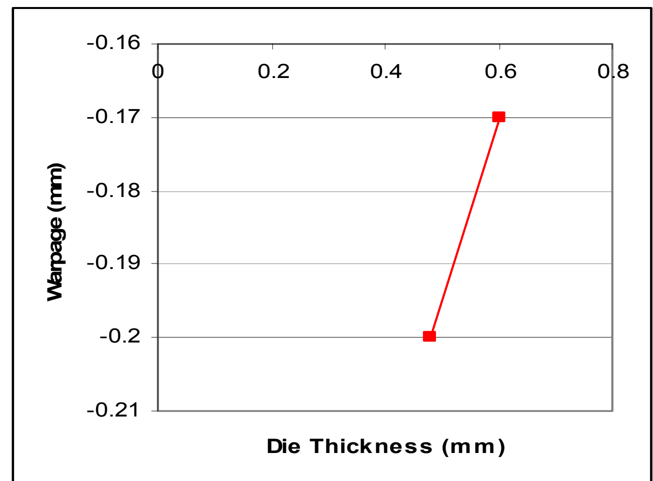

Figure 11. Effect of Die Thickness

Package Size

The effect of package size is shown in Figure 12. The die size remained at 15 x 15 mm. The respective warpages for the three packages, 27-mm, 33-mm and 40-mm, are 0.12 mm (4.8 mil), 0.17 mm (6.8 mil) and 0.23 mm (9.2 mil).

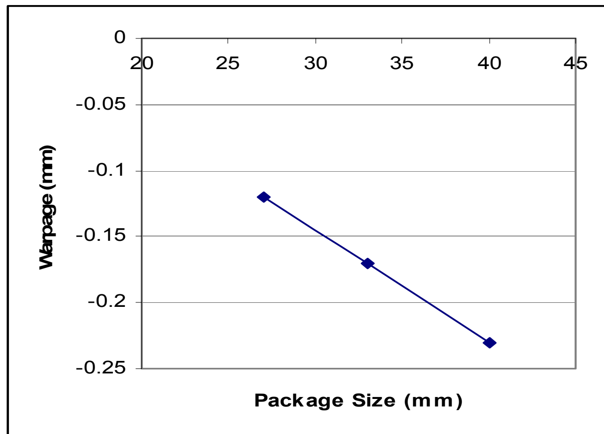

Figure 12. Effect of Package Size

Thermal Interface Material (TIM)

TIM, also called thermal compound or thermal grease, not only provides an efficient thermal path from die to heat spreader, it can also affect warpage. It was found that one with good adhesion may reduce warpage compared with the one with no adhesion, see Figure 13. In addition, modulus plays an important role. With good adhesion, higher modulus is better for warpage as shown in Figure 14. Both can be attributed to a more balance structure surrounding the die.

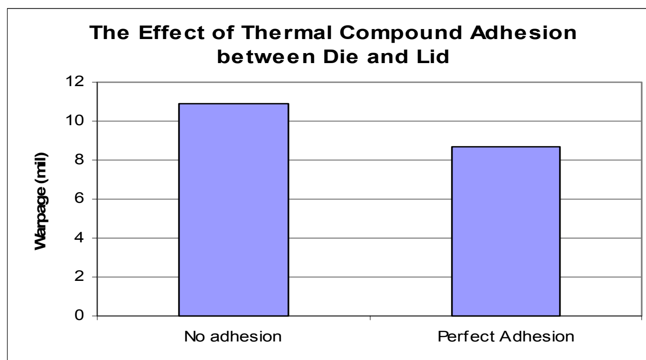

Figure 13. Effect of Adhesion of TIM

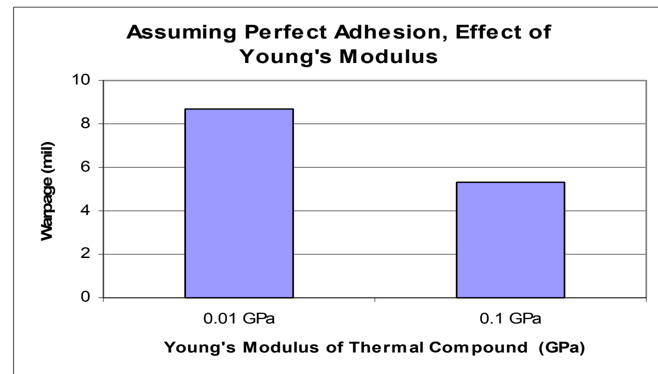

Figure 14. Effect of Young's Modulus of TIM

Discussions

All of the above findings by the model were validated by experiments except for die thickness and TIM. Some other significant factors, which are not disclosed here, are underfill and adhesive.

After implementation in the actual products, the warpage of all the packages had been greatly reduced. The comparisons before and after the implementation are shown in Figure 15.

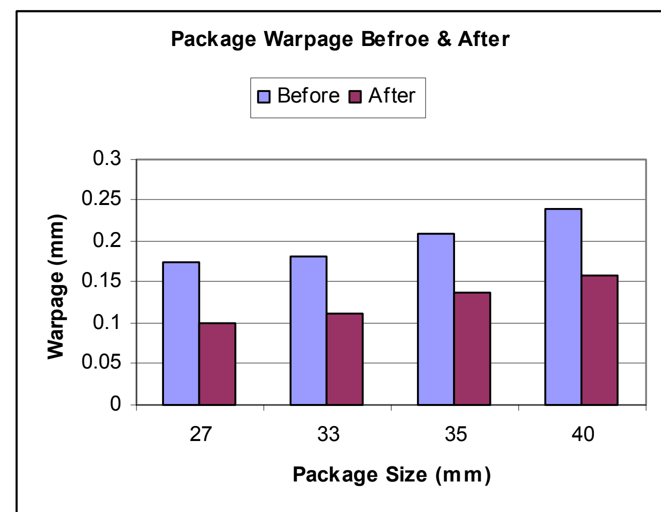

Figure 15. Warpage before and after Implementation

Conclusions

An accurate finite element model was developed to predict the warpage of flip chip BGA. The key to achieve good accuracy is the correct presentations of the properties of underfill and adhesive to the model. Using the model, many factors were investigated. The results were presented for the following factors: heat spreader properties and structure, die size, package size and thermal interface material, which are summarize below:

- Higher CTE and modulus of the heat spreader, less warpage.
- More contacting area between the heat spreader and the substrate, less warpage.

- Larger die, more warpage.
- Thicker die, less warpage.
- Larger package, more warpage.
- TIM with adhesion better than TIM without adhesion.
- For TIM with adhesion, higher modulus, less warpage.

Selective implementation of all the findings to the actual products enabled a significant reduction in warpage across all flip chip BGAs.

Acknowledgments

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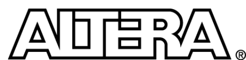

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