



The effects of in-plane orthotropic properties in a multi-chip ball grid array assembly

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Abstract

It has long been recognized that the properties of printed circuit boards and BGA laminates in the out-of-substrate direction differ greatly from the properties in the plane of the substrate. In this paper the variation of in-substrate-plane properties is examined, both in mechanical testing and in finite element analysis. It is shown that the in-substrate-plane coefficient of thermal expansion and modulus of elasticity are influenced significantly by the direction of the traces in the copper layers of the substrate. The impact of these on warpage is explored for a BGA assembly. It is concluded that for multichip products it is necessary to consider the effects that differences in in-substrate-plane mechanical properties may have on the finished product. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

The existence of thermomechanical stress and its effects are commonly recognized throughout the IC industry. Much attention has focused in recent years on warpage and thermomechanical stress damage both within the IC assembly and in the attachment of ball grid array type assemblies to the printed circuit board.

Laminate based packages such as the BGA are significantly more complex in their structure than leaded packages. A leadframe assembly is generally a symmetric structure, and not prone to significant warpage; the number of materials in its structure is usually four—leadframe, silicon die, die-attach adhesive, and molding compound.

By comparison, a BGA assembly is quite asymmetrical in its thickness; furthermore the copper leadframe is replaced by a substrate in which resin, glass-reinforcing mat, copper and solder resist all contribute to the mechanical behavior. The glass-reinforced resin has highly

orthotropic mechanical properties; and the patterning of the copper layers can also add significantly to orthotropic behavior of the substrate.

The BGA substrate structure can accept a number of IC chips, and provide interconnections between them. This has led to many multichip modules in the BGA format. However, the patterning of the copper to provide the interconnections between the chips is of necessity asymmetrical, and in some cases the asymmetry in the copper may be so severe as to have a significant impact on the warpage of the assembly.

Recent measurements of warpage of a multichip BGA assembly revealed saddle-shaped warpage of the assembly. Profiles were measured by laser of the perimeter of a 14 × 22 mm multichip PBGA containing three chips. The actual surface of the substrate was irregular due to the presence of copper traces, although the saddle-shaped warpage was quite evident. Fig. 1 shows a profile taken around the perimeter of the top surface of the molded encapsulant.

The two long edges are hogged (i.e. with center bowed upwards) and the near short edge is sagged (i.e. with center bowed downwards). The highest point in the upwards bow is 19 μm above the corresponding edge of the reference plane, while the lowest point in the sagged edge is 5 μm below it.

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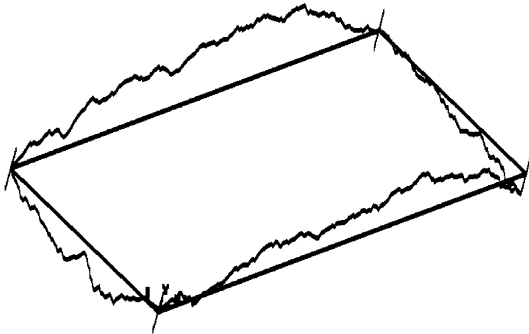


Fig. 1. Vertical profile of perimeter of 14 × 22 mm PBGA package showing saddle-shaped warpage.

This degree of warpage is well within the limits of manufacturing capability. However the saddle-shaped warpage is uncharacteristic of a bimaterial plate, and thus is unexpected in a BGA assembly because the BGA is an approximation of such a structure. Consequently measurements of the mechanical properties of multichip BGA substrates in general use were examined. These showed that the mechanical properties of BGA substrates differ by as much as 25% in the orthogonal directions within the substrate plane. The effect that this difference in in-substrate-plane properties has on warpage of a BGA assembly is examined in this paper.

2. Prior work

A comprehensive review of experimental and analytical methods for the examination of IC systems was presented by Suhir [1]. The importance of analytical modeling was emphasized in regard to understanding the mechanical behavior and enabling the significant factors to be distinguished from the insignificant. A wide-ranging review was then provided of the analytical and numerical modeling of material behavior—primarily of IC assemblies under thermomechanical stresses.

An IC package is composed of a variety of materials which are assembled at elevated temperatures. The materials have differing coefficients of thermal expansion. When the assembly cools to room temperature these differences give rise to thermomechanical stresses. An understanding of the thermomechanical behavior of the simple bimetallic strip is essential to the understanding of corresponding behavior in IC assemblies. Two useful reviews of work in this area were provided by Pionke and Wemper [2] and Kfoury and Wong [3]. Glaser [4] reviewed work on similar structures in which the adhesive bonding material was compliant.

The bimaterial approaches described in the reviews above were extended to the complex structures of BGA

packages in more recent papers by Basaran and Zhao [5] and Guo and Zhao [6]. Researchers also recognized that the BGA laminates had orthotropic properties. Such structures were not modeled readily with analytical tools, and use was made of finite element analysis for this purpose. Hauck et al. [7] Hong and Su [8] and Moore and Jarvis [9] presented analyses in which the differences in properties between the out-of-substrate-plane and in-substrate-plane directions were fully recognized using 3-D FEA modeling.

An analytical approach to the “out-of-modeling-plane” (i.e. the Z-direction as defined in Fig. 2) behavior of materials in IC packaging has been developed over the past few years. Hu and Pagano [10] introduced an artificial coefficient of thermal expansion in the out-of-modeling-plane direction for each material. This permitted a 2-D plane strain analysis to be carried out instead of a 3-D generalized plane strain analysis. The artificial thermal strains were chosen such that the model provided an identical stress field to that of the generalized plane strain problem. Variyam et al. [11] expanded this approach to take the orthotropic properties of the various materials into account using an analytical approach. Both 3-D and 2-D formulations were developed to study the behavior of multilayered structures subject to thermal loading. The 3-D representation permitted the orthotropic properties of each material to be considered in the calculations. For the 2-D representations a special formulation consisting of zero out-of-modeling-plane CTE was presented.

Structural failures within the laminate have been examined by Klingbeil and Bueth [12,13]. An analytical approach was used in which susceptibility to both free-edge debonding and interface crack extension were considered. The objective was to determine the structural combinations most likely to resist delamination. Moore and Jarvis [14] and Moore et al. [15] considered actual failure mechanisms in BGA substrates and the means of investigating them. Kousaka et al. [16] made physical measurements of warpage in PBGA assemblies and concluded that the warpage was closely correlated with the properties of the molding compound.

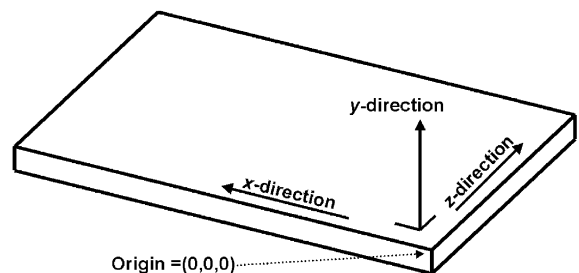


Fig. 2. Orthogonal directions used in this paper.

3. Scope and objectives

In the work that follows, the analyses make the assumption that the material properties are constant with temperature. This assumption is not correct. However it is an acceptable assumption in the context of a study of in-substrate-plane differences in elastic modulus and coefficient of thermal expansion. In this study we set out to explain the phenomenon of saddle-shaped warpage, rather than predict accurately the warpage which occurs.

Similarly the effects of viscoelasticity are not taken into account.

Before discussing this theme further it is necessary to define the orthogonal directions to be used in this paper. The sketch in Fig. 2 sets these out. The later figures in this paper use an orientation similar to that shown in Fig. 2.

In conformance with common practice for the examination of IC structures by finite element analysis, a Cartesian coordinate set is used. The *X*-direction is taken to lie in the plane of the substrate on which the die is attached. The *Y*-direction is taken to be normal to this plane. The *Z*-direction is taken to be the second direction in the plane of the substrate, and is orthogonal to *X*- and *Y*-directions. The 3-D structure is presented with the center of the assembly at the *X*, *Z* origin. In 2-D analyses of IC packaging, generally the *Z*-direction is not modeled, but is addressed by either plane stress or plane strain assumptions.

Warpage of the BGA package prior to board mounting is controlled by the JEDEC specifications for package outlines, and by tighter in-house specifications. For example the JEDEC specification of this package is MS-028-C; it permits a total coplanarity range of 150 μm . The in-house specification is typically 76 μm . Excessive warpage causes failure of contact between the balls of the BGA and the pins in the test socket during electrical testing. Similar failure of contact of warped BGAs will arise with microprocessors and similar removable devices that are used in conjunction with board-mounted sockets.

The effects of regular bi-material deformation on warpage of BGA assemblies are well understood. Careful selection of molding compound can help to minimize the warpage. This paper examines the influence that the in-plane orthotropic properties of the BGA substrate have on the overall warpage of the BGA package. This in-substrate-plane orthotropy is found predominantly in multichip BGA assemblies.

The objectives of this paper are threefold. The factors which influence the orthogonal properties of BGA substrates are examined; the contribution of the copper patterning to the in-substrate-plane properties of BGA substrates is explored; and the effect of this on the warpage of the assemblies is evaluated.

4. Orthotropic behavior of BT substrates

The substrate of a BGA package is generally manufactured from BT resin reinforced with mats of woven glass fiber. Each mat consists of a fabric of orthogonal threads, with each thread comprising of multiple strands of fiber. The core of the substrate usually comprises of one or more such mats. Its two outer surfaces are each sheeted with a layer of copper that is subsequently patterned and etched to create the circuits. Multilayer substrates have additional mats bonded to these patterned layers, usually a single mat per additional layer. Each additional mat has a further outer copper sheet, again patterned to form circuits. Fig. 3 is a cross-sectional photograph of a 4-layer substrate, comprising of three mats in the core and one mat in each of the additional layers. The total thickness of the substrate, including the solder resist layers, was 560 μm .

The fibers parallel to the cross-section can be seen as wavy near-horizontal lines, while the perpendicular fibers are seen end-on. Cross-sections of traces remaining after etching of the four copper layers are also visible. This construction gives rise to greatly differing properties in the *Y*-direction than in the *X*- and *Z*-directions. Reported values [8–10] range from 20 to 26 GPa for in-substrate elastic modulus and 8.3–11 GPa for out-of-substrate elastic modulus. The same sources [8–10] offer 12.4–15.9 ppm/°C for in-substrate TCE, and 52–80 ppm/°C for out-of-substrate TCE. With such large differences it is essential to distinguish between in-substrate and out-of-substrate properties in an analysis of warpage and stress in a BGA assembly.

It has been observed in some physical measurements [17,18] of the mechanical properties of the substrate for multichip BGAs that the modulus of elasticity differs significantly in the *X*- and *Z*-directions (i.e. the in-substrate-plane directions). Generally the glass-fiber mats are manufactured to have symmetrical properties in these directions, and a possible explanation for the difference

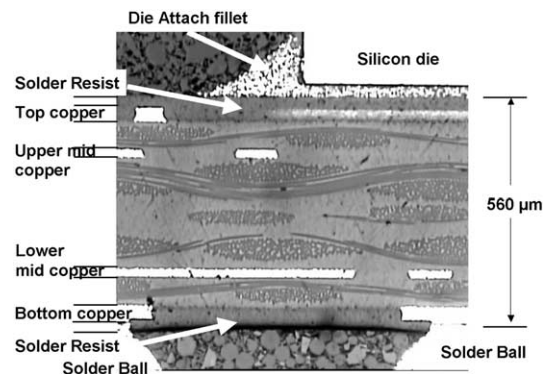


Fig. 3. Cross-section of 4-layer BGA substrate.

lies in the non-symmetrical patterning of the copper traces. The substrates for single chip BGAs are usually designed to have nearly symmetrical copper patterns. However for multichip assemblies, this near symmetry is not always possible because of interconnection requirements between the chips. Fig. 4 is a sketch of the top layer of a 2-layer 2-chip 12×12 mm LFBGA in which the routing between the chips is clearly not symmetrical. The current trend towards multichip modules in a single-chip package outline is bringing increased occurrence of this characteristic.

A simple 3-D finite element model was made of a square two-layer substrate in order to investigate the effects of the orientation of the copper traces. This is shown in Fig. 5. The software used was ANSYS 5.6. In this model the copper was laid out to run continuously from end to end in the X -direction, while in the Z -direction the copper was divided into parallel lines occupying 50% of the total area.

The model had a core $200 \mu\text{m}$ thick, with copper traces on top and bottom of $20 \mu\text{m}$. The end-faces $X = 0$ and $Z = 0$ were set as planes of symmetry. A model size of 2.0 mm in X and Z was sufficient to allow the required data to be extracted. The mean in-substrate-plane properties from [17] were used in this analysis; the Y -direction properties of the substrate were taken from the literature as were Poisson's ratios and Shear Moduli.

Firstly compressive stresses were applied in separate simulations to one or other of the edge faces of the substrate, and from this the modulus of elasticity in each direction was determined. In a third simulation only a temperature change was applied, and the shrinkage in each direction was used to determine the corresponding coefficients of thermal expansion.

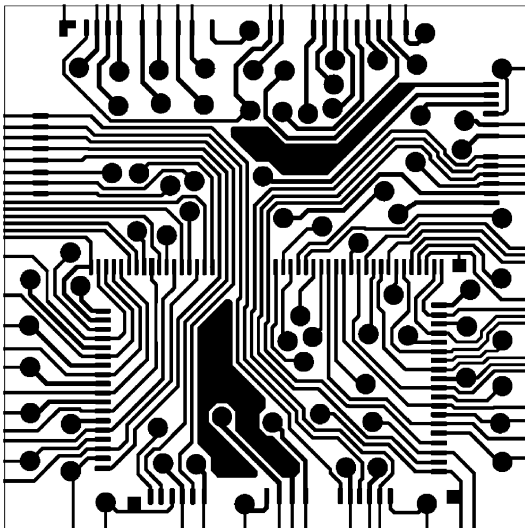


Fig. 4. Complex routing in a 2-chip 12×12 mm LFBGA.

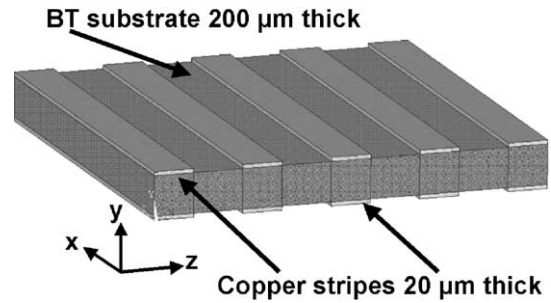


Fig. 5. Model of BGA substrate with orthogonal copper layout.

The moduli of elasticity were found to be 23.0 GPa in the X -direction and 17.5 GPa in the Z -direction. These values are within 3% of the orthotropic values reported in [17]. The TCE was $13.7 \text{ ppm}/^\circ\text{C}$ in the X -direction and $10.9 \text{ ppm}/^\circ\text{C}$ in the Z -direction. This is the orientation of the properties set out in Substrate B in the analyses in the following section.

The higher elastic modulus and TCE in the Z -direction are due to the continuous nature of the copper strips in that direction, coupled with the significantly higher modulus of elasticity of copper. In the X -direction the copper is discontinuous and has less influence on the overall stiffness of the substrate.

5. Effect of orthotropy on warpage and stress

Such large differences in value between material properties in the X - and Z -directions might have a significant impact on the warpage and stress levels in IC assemblies—especially in multichip products in which copper patterning is not symmetric. Accordingly a 3-D simulation of the 3-chip 14×22 mm PBGA was constructed. The device modeled was in fact the one from which the original substrate material properties were physically measured in [17].

The structure of this assembly is described in detail by Moore and Jarvis [9]. For the present analysis a 3-D quarter symmetric model was constructed. The set of material properties used is presented in Table 1 below. The model contained almost 16,000 elements (20 noded brick type), and 70,000 nodes. The thermal loading was a temperature reduction from 175 to 25°C .

Convergence of displacements was verified by solving the structure using 6000 elements, and repeating the analysis with 16,000 elements. The displacements in each analysis were identical to four significant digits, indicating that the smaller model had converged. Nonetheless the analyses reported here were all conducted with the larger model.

Table 1

Full set of material properties used in 3-chip FEA model, including the options relating to alternative CU orientations

	Elastic modulus (GPa)	Minor Poisson's ratio	TCE ppm/°C	Shear modulus (GPa)
Substrate A—Cu continuous in Z-direction				
X (YZ)	17.5	0.39	10.9	3.2
Y (ZX)	8.8	0.11	57	9.0
Z (XY)	23.0	0.39	13.7	3.2
Substrate B—Cu continuous in X-direction				
X (YZ)	23.0	0.39	13.7	3.2
Y (ZX)	8.8	0.11	57	9.0
Z (XY)	17.5	0.39	10.9	3.2
Die-attach	5.5	0.4	45	
Silicon	129	0.278	2.8	
Compound	15.8	0.025	15	

Fig. 6 is an overview of the structure of the model. The molding compound has been omitted for clarity. The nearest corner of the model (0,0,0) is the center of symmetry. One quarter of the middle chip is modeled, with half of one of the outer chips. For simplicity of modeling, both of the chips have the same dimension in the Z-direction, although in reality the middle chip is slightly smaller.

The deformed shapes of the assemblies using the different orientations of substrate properties are presented in Fig. 7. The shading in each case represents displacement in the Y-direction, i.e. the vertical movement of the substrate, and is a close approximation to the warpage.

The displacement of Substrate A is shown in the upper plot; here the copper orientation is in the long direction of the package, i.e. the X-direction, passing underneath all chips. The nearest corner, representing the center of the package, at (0,0,0) has not moved vertically, because the top surface of the substrate at this point was the single fixed point in the analysis.

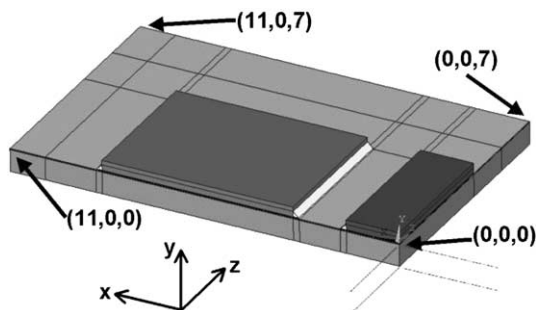


Fig. 6. Overview of a quarter model of 3-chip 14 × 22 mm PBGA.

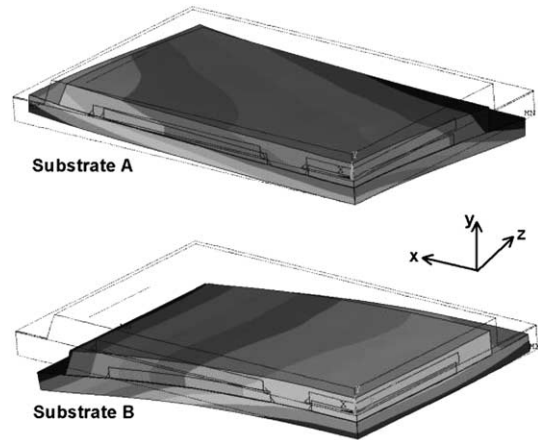


Fig. 7. Plots of deformed shape for one quarter of a 14 × 22 mm PBGA under alternative substrate properties.

It can be seen that the left-hand corner of the model (11,0,0) has deflected upwards. This point represents the middle of the short edge of the package.

On the right-hand side of Substrate A however, the extreme point (0,0,7) has deflected downwards. This point represents the middle of the long edge of the package. The farthest corner at the back of the image (11,0,7) has also deflected downwards, but not as much and lies vertically half-way between the two mid-edge points; this point represents a corner of the package. Table 2 below gives the values of these deflections.

A saddle shape is produced when the centers of adjoining edges are deformed in opposite directions. Generally thermomechanical warpage of multilayer plate-like structures is expected to form a spherical shape. The explanation for the difference between this result and the general expectation lies in the difference in orthotropic properties in the two in-substrate plane directions.

The displacement of Substrate B is shown in the lower plot in Fig. 7; here the in-substrate-plane orthotropic properties are predominantly laid across the short

Table 2

Y-displacement of corners of model of 14 × 22 mm PBGA under alternative substrate properties

		Model corner (mm)			
		X = 0, Z = 0	X = 11, Z = 0	X = 0, Z = 7	X = 11, Z = 7
Substrate A					
Displacement	0	+5.1	−18.6	−7.0	
(μm)					
Substrate B					
Displacement	0	−30.4	−3.9	−27.8	
(μm)					

direction of the package. As before, the near corner of the plot represents the center of the package and has not moved vertically.

In this plot the left-hand corner (11, 0, 0) has moved downwards quite significantly and is the most displaced point of the assembly.

The right-hand corner of the model (0, 0, 7) has also moved downwards, but only slightly. The farthest corner of model (11, 0, 7) has also moved downwards significantly, almost as much as the left-hand point.

It is evident that the deformed shape of the PBGA assembly can be affected significantly by the orientation of the copper traces in the substrate. The material properties in Substrate B were those measured from the substrates of the actual product. Fortunately, the warpage was within acceptable limits in the actual product.

In Substrate B the corner (11, 0, 7) represents all four outer corners of the entire assembly. A plane is defined by these four corners, which is equivalent to the reference plane of the actual device described in Fig. 1. In the simulations above, the reference plane for Substrate B lies 27.8 μm below the origin. The center of the long edge of Substrate B lies approximately 23 μm above this reference plane, and the center of the short edge lies approximately 2.5 μm below it. This is comparable with the actual measurements, with corresponding displacements of 19 and 5 μm , respectively.

6. Conclusions

The study serves to highlight that the classical deformation theory of bimaterial plates under temperature change is not appropriate for analysis of warpage of multichip BGA assemblies.

The derived values of warpage may not be exact because of the assumptions set out in Section 3. In addition, this study used an extreme example of orthotropy in the layout of the copper traces in order to highlight the effect. Nonetheless, the saddle-shaped warpage determined in the finite element analysis approximated to the actual warpage measured in the corresponding BGA assembly.

Differences in in-substrate-plane orthotropic properties of BGA substrates due to differences in orientation of copper traces were shown to give rise to significant differences in deformed shape of the assembly. (It is quite probable that similar effects will be observed in PCBs).

Stress analysts and product designers must take into account that substrate properties may differ in X - and Z -directions, especially for multichip products or products with imbalanced bond-outs around the die periphery. The effect of these is to create saddle-shaped warpage. In certain designs the overall result will be more severely

warped that would be inferred in planar isotropy. A study on this [19] is in preparation by the authors.

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