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Thermally induced deformations in die-substrate assembly

Milena Vujošević *

Abstract

The work focuses on the thermally induced deformations caused by the processing of Flip Chip Ball Grid Arrays (FCBGA). Analytical expressions for substrate displacements are derived based on the Plate Theory and Suhir's solution for stresses in tri-material assembly. The validity of the model is established by comparing the analytical solution to the numerical finite element results as well as to the experimental data. The benefits of the proposed model are twofold: 1) it provides a tool for fundamental understanding of the deformation process of interest, and 2) has a predictive capability. More specifically, an analysis is presented on the nature and degree of influence that different geometric and material parameters have on the substrate deflections, as well as a "Warpage Contour Plot", proposed as a tool for warpage prediction that can be easily utilized in the early stages of the design process.

Keywords: die-substrate assembly, flip chip BGA, substrate deflection, warpage

1 Introduction

A Flip Chip Ball Grid Array (FCBGA) is an electronic package formed by attaching the Integrated Circuit (IC) to the substrate (Fig. 1). It is a special type of a BGA package where the die is flipped (with circuitry facing the substrate) in order to provide the shortest possible chip-to-package interconnection distance. This improves the electrical performance because it minimizes impedance, resistance, and parasiting inductance. The functions of an FCBGA, like the function of any IC package, are to protect, power, and cool

*Intel Corporation, Folsom, CA, USA, e-mail: milena.vujosevic@intel.com

the microelectronic device and to provide electrical and mechanical connection between the device and the outside world.

The electrical and mechanical connection between an IC and a substrate typically involves solder interconnections, although alternate material system can also be used [1]. Often, underfill encapsulants are applied at the interface between the chip and the substrate in order to lower thermomechanical stresses on the interconnections and to protect the interconnections from environmental effects. After the package is manufactured, solder balls are attached to the bottom of the substrate to enable mechanical and electrical connection of the package to the Printed Circuit Board (PCB).

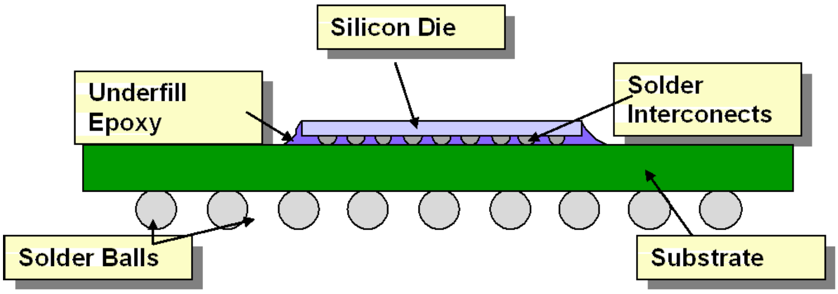

Figure 1: Flip Chip Ball Grid Array (FCBGA)

During the manufacturing of an FCBGA, materials are bonded at an elevated temperature, and then the assembly is cooled back to room temperature. Because the materials involved have different thermomechanical properties, the bonding process introduces stresses and deformation in the FCBGA package.

Deformations that are of particular interest for package performance are the out of plane displacement of the substrate. These displacements are in electronic packaging literature often referred to as warpage. The number W that is a measure of warpage is a minimum distance between two parallel planes encompassing the bottom plane of the substrate (Fig.2).

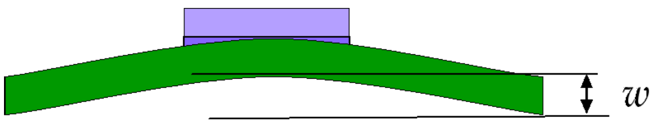

Figure 2: Measure of warpage

Warpage is an important reliability concern for FCBGA packages because it can compromise proper assembly of the package to the printed circuit board. Warpage that is too large results in one of the two scenarios (Fig. 3):

1. solder balls do not crate proper contact with the board preventing formation of electrical connection (open circuit), or

2. closely spaced balls get squashed during the assembly to the extant that they touch each other creating a short circuit. From the package performance and reliability standpoint, each of the above scenarios represents a failure. Because of this, design for warpage is one of the very important stages in the FCBGA package development.

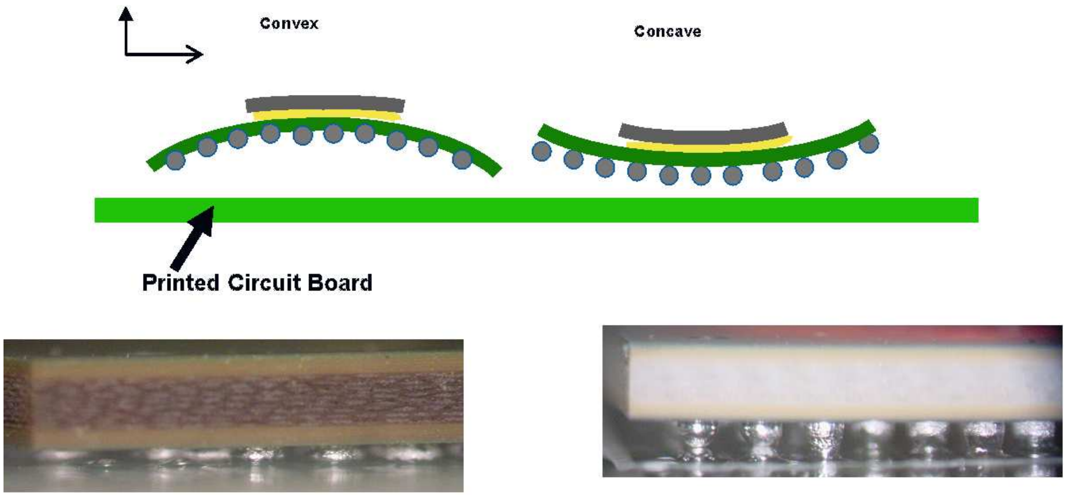

Figure 3: Package before the assembly to the board (Top). Package after the assembly: a) Bridging of solder balls causing short circuit connection (bottom left) and b) Bond between the package and the board not formed properly resulting in an open electrical connection (bottom right)

The warpage criterion widely adopted in the solid-state industry is based on the JEDEC Standard [2]. JEDEC standard defines the maximum FCBGA warpage as a function of solder ball size and pitch (minimum distance between the neighboring solder balls). Since warpage is temperature dependent, the criterion in [2] specifies a limit that peak deflection of the package should not exceed *at room temperature*, before it is assembled to the board. Whether a package will satisfy JEDEC criterion depends on many parameters related to package design and processing. In the package development process it is important to understand the impact of these parameters and to be able predict the warpage.

In this work, an analytical solution for FCBGA warpage is proposed. The model provides a tool for estimating the level and the nature of influence of different material, geometric and processing parameters. In addition, the solution is conveniently adapted for easy warpage prediction through the creation of the Warpage Contour Plots.

2 Analytical Model

A model that is adopted in this work, considers an FCBGA package to be a tri-layered material assembly (Fig. 4). Warpage that takes place is a result of the stresses that develop at the material interfaces after the rigid bonding is established. The whole process starts when at elevated temperature the middle layer (material no.2) solidifies and creates a rigid connection between the die (material no.1) and the substrate (material no.3). Relative motion is therefore prevented between the mating surfaces of the die and the substrate, forcing them to deform together.

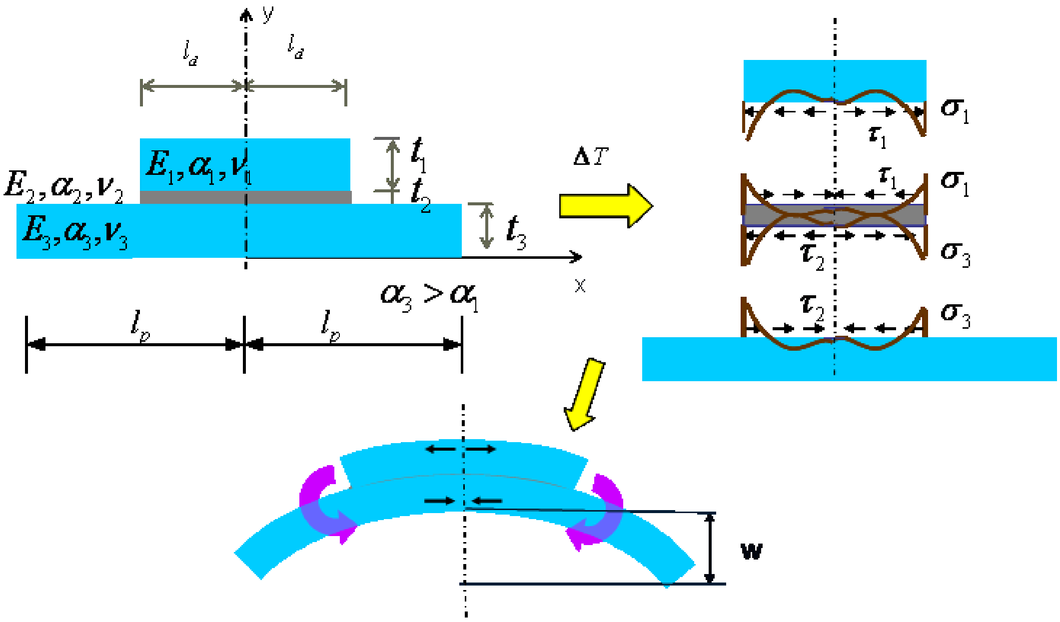

Figure 4: Deformation during the FCBGA assembly

For the organic substrates, their coefficient of thermal expansion is significantly larger than the coefficient of thermal expansion of silicon ($\alpha_3 > \alpha_1$). Therefore, during the cooling of the assembly to room temperature the substrate would tend to contract more than the die. This results in the bending of the assembly in a convex shape (Fig.4).

Several analytical formulations have been proposed that predict the stress distribution along the interfaces of the die-substrate assembly [3-7]. These formulations are all based on Timoshenko's theory of bi-metallic thermostat [8]. The proposed models, although with some controversies [9], have provided an insight into the fundamentals of thermal stresses in a die-substrate assembly, as well as the identification of important parameters and their influence on the stress state.

One of the well recognized formulations for the stresses in die-substrate assembly was developed by Suhir [4-7]. This solution is based on the small deflection plate theory, linear elastic isotropic material behavior, and following assumptions:

1. the thickness of the adhesive material is small in comparison to the thickness of the adherents,
2. adhesive material has a compliance that is significantly larger than the compliance of the die and substrate,
3. the perfect bonding is established at the interfaces, and
4. each layer of the assembly acts as a spherically bent plate.

According to this solution, the stresses at the interfaces (Fig. 4) are defined as follows [3,4]:

The stress along the bottom of the die is

$$\sigma_1 = \frac{\Delta\alpha\Delta T}{\lambda t_1}\left(1 + 3\frac{t}{t_1}\frac{D_1}{D}\right)(1 - \frac{\cosh kx}{\cosh kl_d}),$$

the stress along the top of the substrate:

$$\sigma_3 = -\frac{\Delta\alpha\Delta T}{\lambda t_3}\left(1 - 3\frac{t}{t_3}\frac{D_3}{D}\right)(1 - \frac{\cosh kx}{\cosh kl_d})$$

and the shear stress:

$$\tau_2 = K\frac{\Delta\alpha\Delta T}{\lambda}\frac{\sinh kx}{\cosh kl_d}.$$

In the above equations:

$$\Delta\alpha = \alpha_3 - \alpha_1$$

is the difference in the coefficients of thermal expansion (CTE) of the substrate and the die,

$$\Delta T = Troom - Tg$$

is the temperature difference to which the assembly is exposed,

$$D_i = \frac{E_i t_i^3}{12(1-\nu_i)}$$

is flexural rigidity of the plate (material *i*, *i=1,2,3*) in spherical bending[1]

$$\lambda = \frac{1-\nu_1}{E_1 t_1} + \frac{1-\nu_3}{E_3 t_3} + \frac{t^2}{4D}$$

[1]The flexural rigidity defined in this way represents a modification of Suhir's solution introduced by Tsai et al. [9].

is the axial compliance of the assembly,

$$\mathrm{K} = \frac{t_1}{3G_1} + \frac{2t_2}{3G_2} + \frac{t_3}{3G_3}$$

is the interface compliance, and

$$k = \sqrt{\frac{\lambda}{\mathrm{K}}}$$

represents longitudinal compliance. Symbols E_i, G_i and ν_i are elastic constants: Young's modulus, Shear modulus and Poisson ratio of material $i (i = 1, 2, 3)$, respectively.

Coefficient of thermal expansion of the attachment material does not enter into the relations for the stresses in the assembly, as long as the thickness and/or the modulus of the adhesive are small compared to that of the adherents [4].

The package deformations that take place are a result of stresses that develop due to the change in temperature. To determine the deflections of the substrate it is assumed that the displacements are small, and that substrate in the die shadow region deforms in spherical bending [10]. The objective of the model is not to determine the whole deformation field but to find peak deflection and relative displacements along the characteristic directions, particularly the diagonal (since the corner of the package is the point undergoing the largest relative displacement).

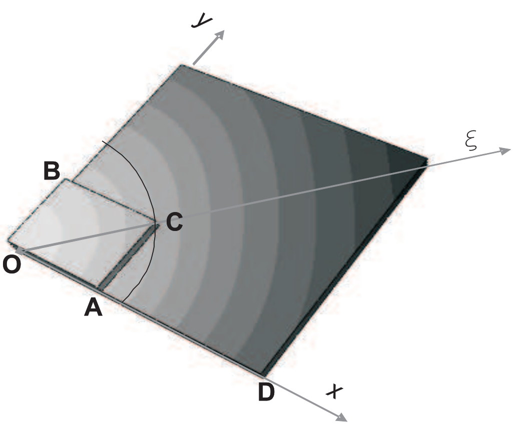

Figure 5: Quarter of the package with deformation contours

In spherical bending, the curvature in the region O-A-B-C is constant and directly related to the bending moment [11]. From the stresses that act on the assembly, the curvature along the path O-A can be determined to be [7]:

$$\frac{1}{\rho(x)} = \frac{t\Delta\alpha\Delta T}{2\lambda D}\left(1 - \frac{\cosh kx}{\cosh kl_d}\right) \tag{1}$$

Through the integration the out of plane displacement w along the x axes in the region O-A, are obtained [9]:

$$w(x) = \frac{\Delta\alpha\Delta Tt}{2\lambda D}\left(\frac{x^2}{2} - \frac{\cosh kx - 1}{k^2\cosh kl_d}\right) \tag{2}$$

The displacement along the x axes for $x > l_d$ can be approximated as:

$$w(x) = w(l_d) + \frac{dw}{dx}|_{x=l_d}(x - l_d) \tag{3}$$

which for $x = l_p$ becomes [10]:

$$w(l_p) = \Delta\alpha\Delta T\frac{t}{2\lambda D}(\frac{1}{2}l_d^2 - \frac{1}{k^2} + \frac{1}{k^2\cosh(kl_d)} + (l_d - \frac{tgh(kl_d)}{k})(l_p - l_d)) \tag{4}$$

To evaluate the displacements along the package diagonal the following considerations about the geometry of deformation are being made. Since the deformations of the substrate in the die shadow region are of the spherical bending type the out of plane displacement $w(x, y)$ in this region are defined as [11]:

$$w(x, y) = \frac{M}{2D(1 + \nu^2)}(x^2 + y^2)$$

At point C, the displacement becomes

$$w_C = w(x_C, y_C) = \frac{M}{2D(1 + \nu^2)}x_C^2 + \frac{M}{2D(1 + \nu^2)}y_C^2 =$$

$$\frac{M}{2D(1 + \nu^2)}x_A^2 + \frac{M}{2D(1 + \nu^2)}y_B^2 = w_A + w_B \tag{5}$$

Indicating that the vertical displacement of point C is equal to the sum of displacements of points A and B (Fig.5); For the square die these displacements are identical ($x_C = x_A = y_C = y_B$ and $w_A = w_B$) and therefore $w_C = 2w_A$ i.e.

$$w(l_d\sqrt{2}) = 2w(l_d)$$

Similarly as in the case for displacement along the horizontal axes x, it was assumed that there is a continuity of slope at point C, and the slope outside the die region is constant. The displacement along the diagonal, C-E, for $\xi \geqslant l_d\sqrt{2}$ is then:

$$w(\xi) = w(l_d\sqrt{2}) + \tfrac{dw}{dx}|_{x=l_d\sqrt{2}}(\xi - l_d\sqrt{2}) = 2w(l_d) + \tfrac{dw}{dx}|_{x=l_d}(x\sqrt{2} - l_d\sqrt{2}) \tag{6}$$

From (2), (4), and (6), deflection along the diagonal path C-E becomes

$$w(\xi) = \Delta\alpha\Delta T\frac{t}{2\lambda D}\left(l_d^2 - \frac{2}{k^2} + \frac{2}{k^2\cosh(kl_d)} + (l_d - \frac{tgh(kl_d)}{k})(\xi - l_d\sqrt{2})\right) \tag{7}$$

Peak warpage (maximum out of plane displacement) $W = w_{max}(\xi) = w_E$ can be obtained from the Eq. 7 for $\xi = l_p\sqrt{2}$.

$$W = \Delta\alpha\Delta T\frac{t}{2\lambda D}(l_d^2 - \frac{2}{k^2} + \frac{2}{k^2\cosh(kl_d)} + (l_d - \frac{tgh(kl_d)}{k})(l_p - l_d)\sqrt{2}) \tag{8}$$

Comparison between the analytical expression for deflection along the diagonal path (Eq. 7), and a solution obtained using the numerical analysis based on the finite element method (FEM) is presented in Fig. 6. The data used for calculation are summarized in Table 1. The very good agreement is found between the two different theoretical formulations (solid mechanics approximation vs. finite element method). Thus, it can be concluded that the analytical model provides a reliable framework for the understanding of the underlying physical mechanisms in the warpage problem as well as for the warpage prediction.

Table 1: Material properties, thickness and bending stiffness of the assembly components

	Young's modulus (MPa)	Poisson Ratio	CTE [ppm/C]	Thickness [mm]	D [Nmm]
Die	130 000	0.28	2.5	0.79	7418.4
Underfill	8300	0.3	31	0.085	0.6068
Substrate	16400	0.2	14.3	1.17	2736.09

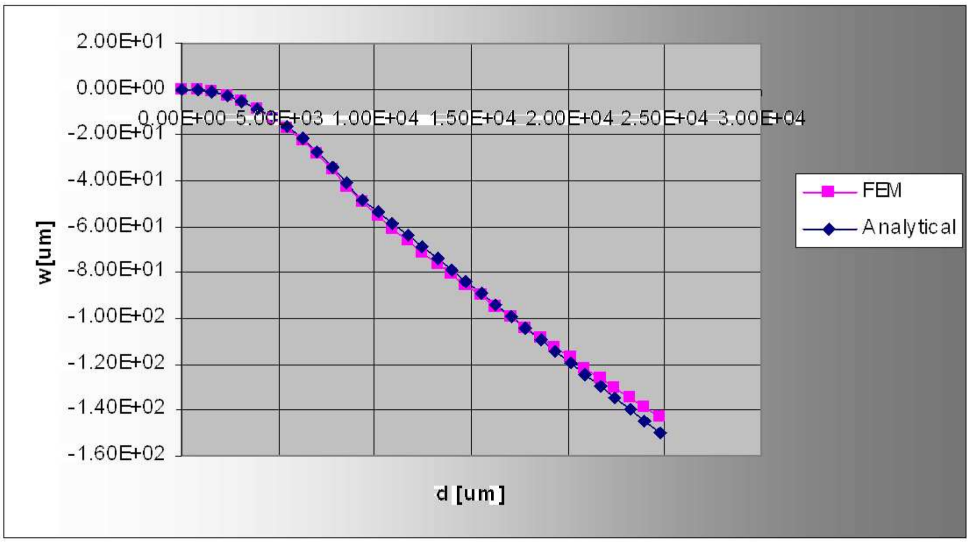

Figure 6: Comparison between the analytical [Eq. 3] and FEM results (package size 35mm; die size 13.2mm; material properties and thickness listed in Table 1)

3 Application of warpage equation: Influence of material and geometric parameters

Developed model lends itself easily to parametric study on the effects that different material and geometric characteristic have on the FCBGA warpage. Several important parameters are considered: the coefficients of thermal expansion, underfill glass transition temperature, elastic properties of the components, the thickness and the size of the die and package (substrate).

3.1 Coefficient of thermal expansion

First observation from the warpage equation (Eq. 8) is that coefficient of thermal expansion of the middle layer has no impact on warpage. The adhesive layer is much thinner than the adherents (die and substrate) and it's Young's modulus is typically significantly smaller than Young's moduli of other two components. Because of this, the in-plane compliance of the middle layer is significantly larger than the in-plane compliance of the adherents. Therefore, the middle (adhesive) layer is subjected to shear only. Consequently the adhesive layer coefficient of thermal expansion does not affect stresses in the assembly and therefore out of plane deformations.

Coefficients of thermal expansions of the adherents, however, do impact warpage but only through their difference $\Delta\alpha$. Since the top layer (layer 1) in electronic packaging is typically a silicon die, the coefficient of thermal expansion α_1 does not change. Therefore, to reduce warpage, the CTE of the substrate needs to get closer to the CTE of the die.

3.2 Glass transition temperature of underfill

Stresses at the interfaces and deformations of the assembly are proportional to the temperature difference ΔT between a "current" state and a stress-free state. In the case of warpage as defined by JEDEC, the "current" temperature is room temperature to which the assembly is cooled down from the underfill curing temperature. The stress free temperature is the glass transition temperature Tg of the underfill, since this is the temperature at which the underfill epoxy solidifies and creates a rigid bond between the die and the substrate. For a typical epoxy, the glass transition temperature is much higher than the room temperature. Therefore, a reduction in warpage can be achieved by reducing $\Delta\mathrm{T} = Troom - Tg$, i.e. by decreasing the glass transition temperature of the underfill. This can be accomplished either through a selection of a different epoxy material or through adjustment of the parameters of the curing process.

3.3 Elastic properties

Regarding the material elastic properties, the influence of Young's modulus and Poisson ratio on warpage is considered. Figure.7 illustrates the effect of the Young's modulus of the layers in the assembly. In electronic packaging application the top layer represents a silicon die, with the Young's modulus that remains relatively unchanged, typically 130GPa (denoted in Fig.7, bottom-left). Nevertheless, effect of the properties of the top component is shown here because the application of the model can be extended to other applications involving a tri-material assembly.

For a given assembly geometry and a given adhesive, there is a Young's modulus substrate to die ratio that maximizes the warpage. The warpage can be reduced by using substrates of very small modulus, and to some extant by using high modulus substrates. This is not surprising because there is a tradeoff between a more compliant and a stiffer substrate. Although a more compliant substrate results in smaller interfacial stresses such a substrate is easier to deform. On the other hand, stiffer substrate generates higher interfacial stresses but it is more difficult to deform, thus possibly resulting in smaller warpage. Precise level to which substrate modulus will affect warpage depends on other parameters as well. For the particular set of component sizes and thicknesses, warpage was maximized when the substrate modulus

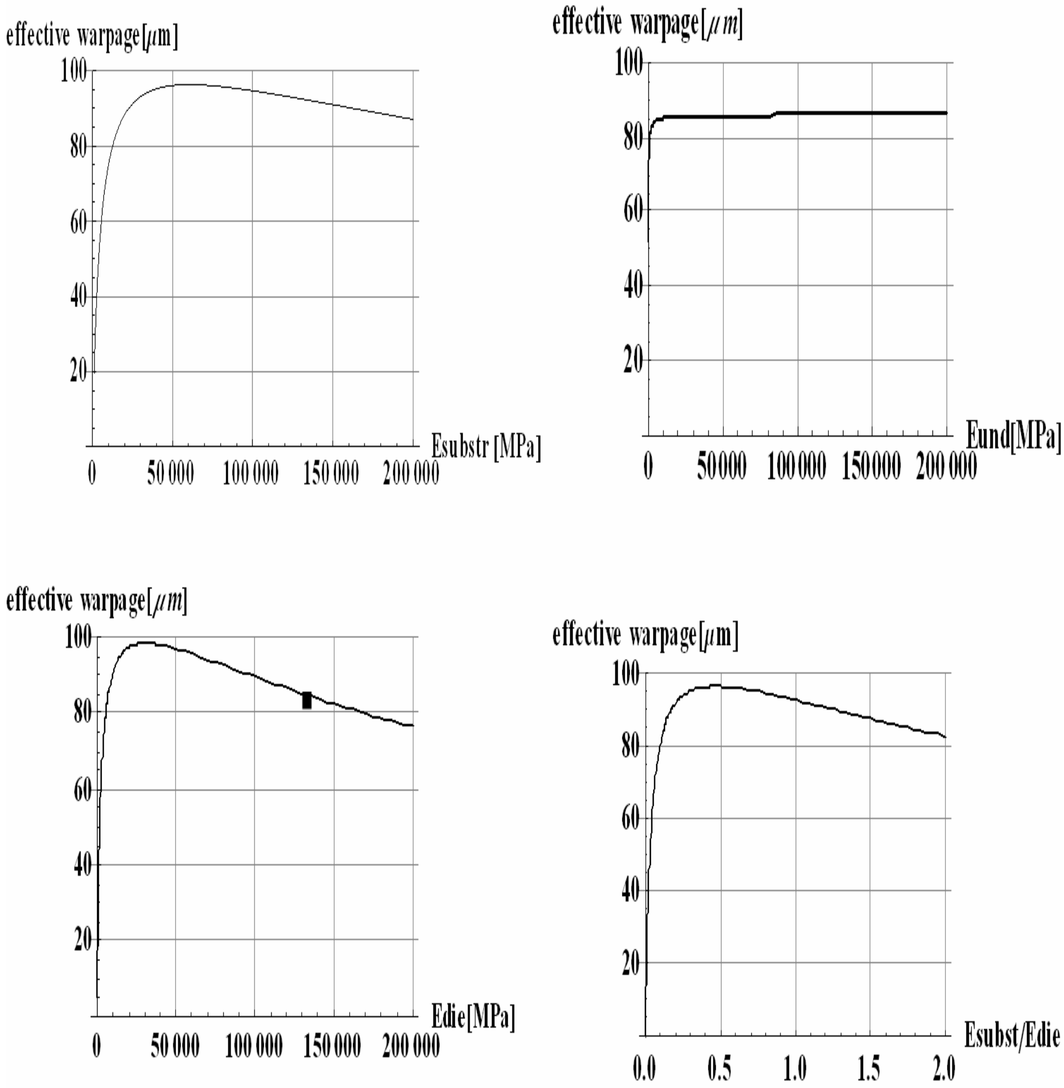

Figure 7: Effect of Young's modulus of package components on warpage.

was about 0.4 of the die modulus (Fig.7).

Young's modulus of underfill above certain value has a week effect on warpage. For smaller levels, however, a sharp increase in compliance of the adhesive causes a significant decline in warpage .

Effect of Poisson's ratio of the assembly components on warpage seem to be quite small (Fig. 8).

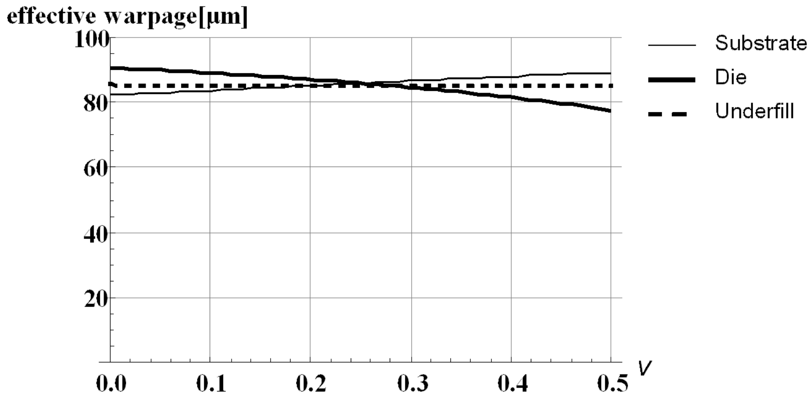

Figure 8: Effect of Poisson's ratio on warpage

3.4 Thickness of individual components

Thickness of the components as a relevant parameter in warpage is depicted in Figure 9. There is a clear trend exhibited by underfill thickness: warpage can be reduced by increasing the thickness of this comparatively compliant middle layer. For the die and the substrate, however, the situation is different: for a given package configuration there is a die thickness as well as a substrate thickness that maximizes the warpage. Changing the thickness (either decreasing it or increasing it) will reduce the warpage. It is particularly useful to have

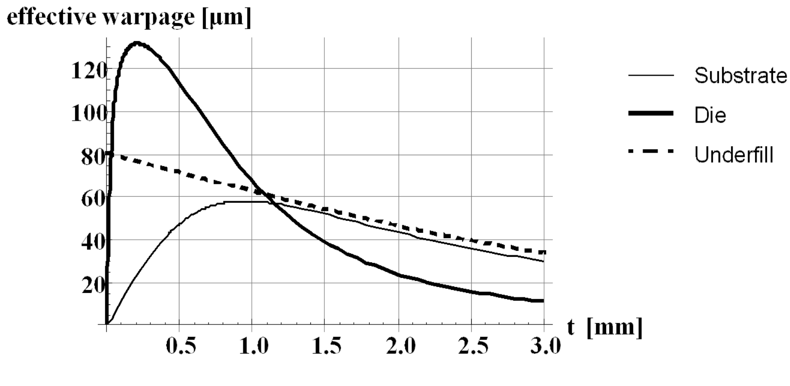

Figure 9: Effect of thickness of individual layers

information on how substrate-to-die-thickness ratio affects warpage, so that possible adjustment in the design may be applied. The impact of this thickness ratio on warpage is a function of other parameters. For example, Fig.10 illustrates how warpage dependence on the thickness ratio is impacted by the substrate Young's modulus. More compliant substrate maximizes warpage for larger thickness ratio. If the objective of the design is to reduce warpage and if there is a room for adjustment of die and/or substrate thickness a graph like the one in Fig.10 can suggest the appropriate directions. It is interesting

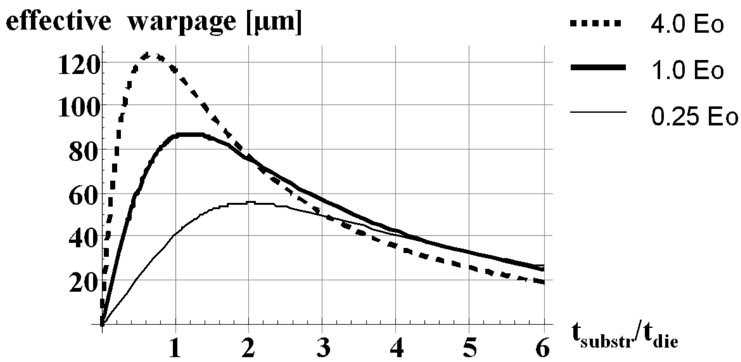

Figure 10: Effect of substrate to die thickness ratio

to notice that substrate stiffness has a negligible effect beyond a certain value of the thickness ratio. In this particular case (package size 37mm and die size 13.2mm) when substrate is more than 3 times thicker than the die, both compliant and stiff substrate provide about the same warpage.

3.5 Package and die size

Package size and die size are the parameters frequently been changed/adjusted in the early stages of the design process due to many factors related to IC performance, package electrical performance and its mechanics reliability, and package application. Based on Eq.(8), it can be concluded that the warpage varies linearly with package size and it is approximately proportional to the second power of the die size (for sufficiently large kl_d , [10]), (Fig.11).

4 Predictive capability: The warpage contour plot

In order to facilitate the predictive capability, the equation (8) is plotted in the **warpage- Ldie-Lpack** space. The resulting 2D contour plot is presented on Fig. 12. A plot like this can easily be generated for the selected material, substrate thickness, and die thickness. Very often, important decisions need to be made regarding the package size and the die size. By using the Warpage Contour Plot, a designer can quickly estimate the warpage number for the

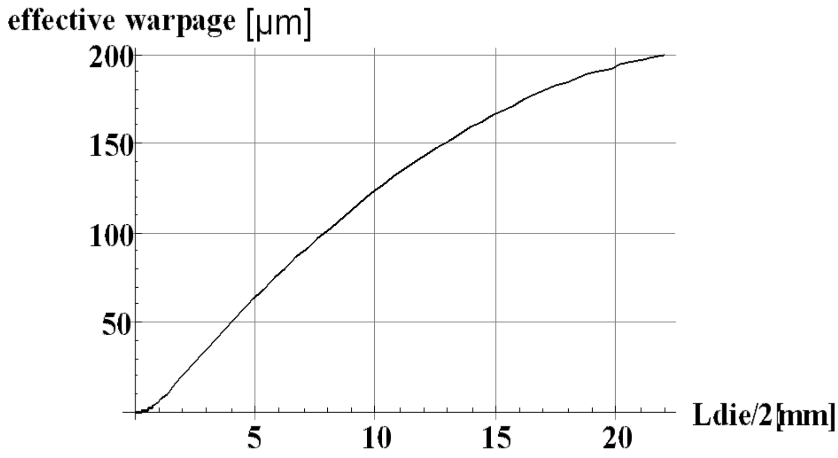

Figure 11a: Effect of die size. Effective warpage $W_{eff} = W * 10^3/\Delta\alpha\,\Delta\mathrm{T}$

Figure 11b: Effect of package size. Effective warpage $W_{eff} = W * 10^3/\Delta\alpha\,\Delta\mathrm{T}$

selected die size/package size pair. The number obtained from the plot is the effective warpage *Weff*, which needs to be multiplied by a factor $p = \Delta\alpha\Delta\mathrm{T}10^{-3}$ to obtain the actual warpage. Moreover, since the contours in Fig.12 are independent of temperature, the peak deflection can be computed for any desired temperature by adjusting the multiplier p. The plot is also independent on the CTE difference $\Delta\alpha$, and therefore the same plot can be used for substrates with different CTE's.

The application of Warpage Contour Plot is illustrated in Fig 12. for two different die size, package size combinations. The warpage numbers at room temperature are estimated from the Warpage Contour Plot. For comparison, the warpage is also computed using the finite element mode. In addition, the experimentally determined peak warpage for one package is listed in Table 2 (test was performed using Moire Interferometry). The comparison of the

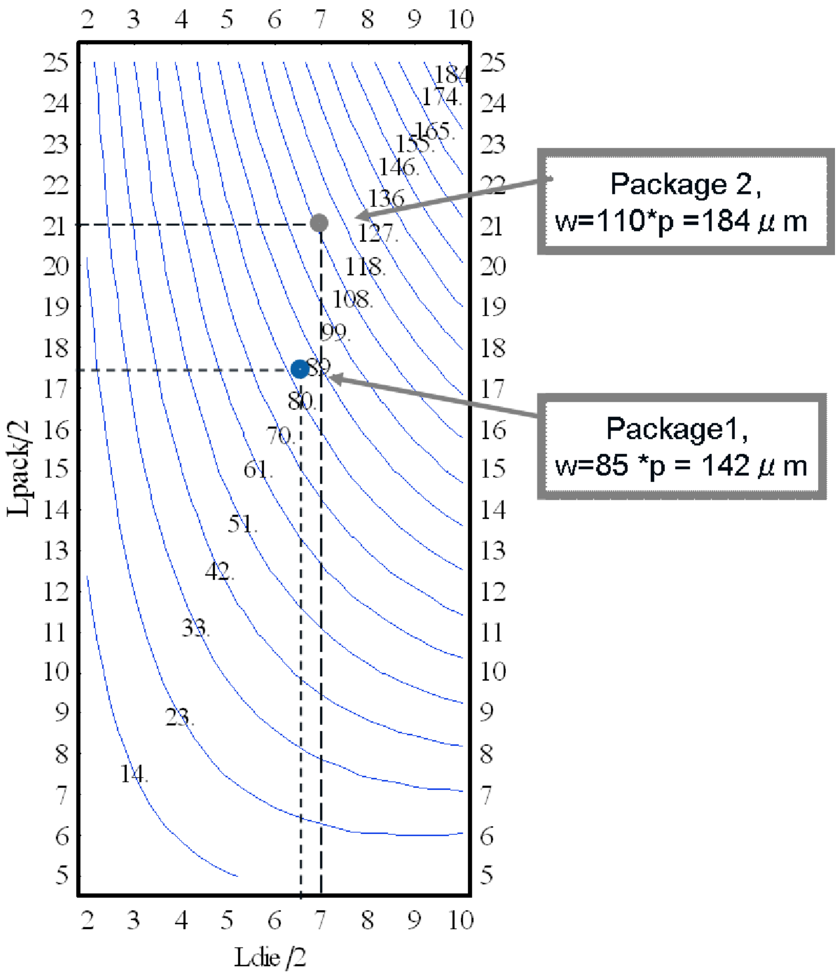

Figure 12: Warpage Contour Plot. Input is half of the die size and half of the package size [in millimeters]. The output is effective warpage in microns. To obtain the actual warpage, effective warpage needs to be multiplied by the parameter $p = \Delta\alpha * \Delta T * 10^{-3}$

results of this simplified model to the more detailed FEM data as well as to the experimental data confirms that the model has a very good predictive capability. It is important to note that the model presented in this paper is

Table 2: Comparison of the analytical with the numerical /experimental warpage data

	Package 1	*Package* 2
Ldie [mm]	13.2	13.97
Lpack[mm]	35	42.5
Warp. Plot μm (mil)	*142* (5.6)	*184* (7.2)
FEM μm (mil)	*138* (5.44)	*178* (7.0)
Test μm (mil)	n/a	*193* (7.6)

applicable to tri-material assemblies that undergo small displacements during the change of temperature. In the case of the FCBGA packages this indeed is the case in almost all applications of practical interest.

5 Conclusions

An analytical solution for warpage has been proposed. The principal benefit of such a model is its generic nature as opposed to usually generated numerical point solutions. The model enables the fundamental understanding of the physics of the temperature dependent package deformation process and clearly illustrates the impact that different geometric and material parameters have on the out of plane displacement of the package. Although based on some simplifications and approximations, the model shows a very good agreement with the experimental end more detailed numerical modeling data. The Warpage Contour Plot which has been generated from the warpage equation represents an easy-to-use tool for quick and reliable estimate of FCBGA warpage, that can be particularly beneficial in the early stages of the design process.

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Termičke deformacije u strukturi silicijumskog čipa i supstrata prouzrokovane procesom montaže

Rad se bavi deformacijama koje promena temperature izaziva tokom procesa montaže silikonskog čipa sa metalnim kuglicama (*Flip Chip Ball Grid Arrays*). Izvedeni analitički izrazi za pomeranja supstrata bazirani su na Teoriji ploča i Suhirovom rešenju za napone u tro-materijalnoj strukturi. Tačnost modela je ustanovljena uporedjivanjem rezultata iz izvedenih jednačina sa numeričkim rezultatima dobijenim korišćenjem metode konačnih elementa i sa eksperimentalnim podacima. Novi model ima dvojnu ulogu: (1) omogućava fundamentalno razumevanje razmatranog procesa deformacija i (2) omogućava predvidjanje ovih deformacija.

U radu se prezentira analiza uticaja koje različiti geometrijski i materialni parametri imaju na deformacije supstrata. Specijalno razvijene mape ("Warpage Contour Plot") predložene su kao sredstvo za predvidjanje maksimalnih pomeranja supstrata. Primena ovih mapa može biti od posebne važnosti u ranim fazama *FCBGA* dizajna.

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