Topography and Deformation Measurement and FE Modeling Applied to substrate-mounted large area wafer-level packages (including stacked dice and TSVs)

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***Abstract*-Topography and Deformation Measurement and FE Modeling were applied for characterization of the warpage vs. temperature behavior of several different die stacks, with or without Through Silicon Vias, for sample temperatures from 25°C…250°C. The warpage behavior is of fundamental importance for the lifetime and reliability expectation of the stack.**

I. Introduction

Mounting of wafer-level packages into conventional PCB substrates poses the risk of excessive warpage and thermomechanical stress, owing to the substantial mismatch in Coefficient of Thermal Expansion (CTE) between Si and standard PCB materials [1]. Furthermore, 3D stacking of dice is one of the most interesting options for further increasing the performance of electronic components, while simultaneously shrinking their size. However it involves several technical challenges, such as the thinning of the top die without getting into trouble due to excessive die warpage, or the failure free manufacturing of Through Silicon Vias (TSVs) [2].

The present study concerns the investigation of the (PCB-mounted) sample warpage as a function of the sample temperature, for a variety of monolithic and stacked die samples. Minimizing the die warpage for all relevant temperatures the stack might be exposed to during manufacturing as well as its entire life time is of particular interest for decreasing the manufacturing failure rate and increasing the reliability expectation. In this paper we focus on the influence of the die thickness on the warpage vs. temperature characteristics of various samples, an example of which is shown in Fig. 1. Si die area was approximately 90mm^2 in all cases, whilst a variety of thicknesses and stacking configurations were considered. A second point of interest is the potential influence of TSVs on the warpage vs. temperature characteristics. The die warpage has been measured experimentally for a wide temperature range. The obtained values are compared to the results of FE modeling of the die topography, for the same temperature range. The obtained die warpage values are very small, in the order of some few µm, and only weakly varying with temperature. However, the good correlation of results between experimental and numerical analysis allows us to cross-validate both analysis techniques, and thus the results themselves.

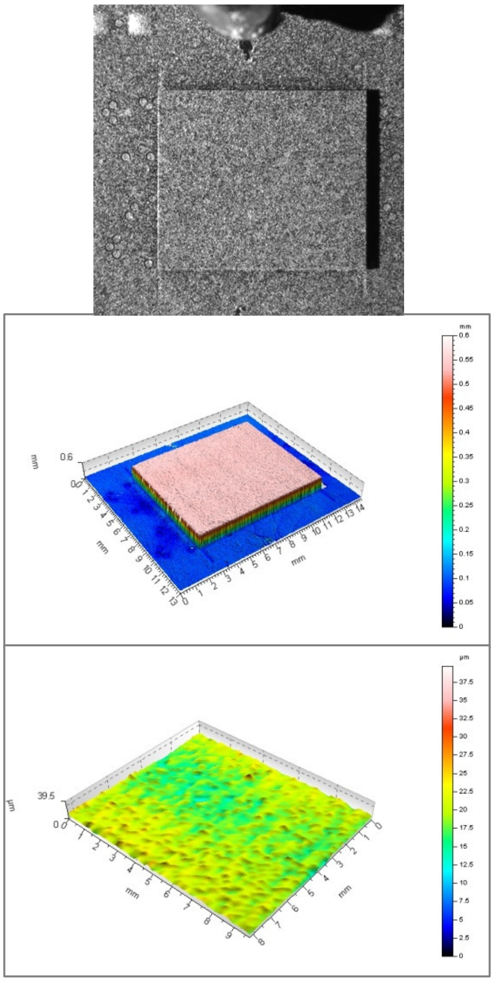

Fig. 1: Top: Photography of the PCB with the stacked die visible in the centre. Centre: 3D topography of the entire sample, obtained by TDM. The total depth of view (full color scale) is 0.6 mm. Bottom: Software zoom on the central die topography. The total depth of view represents 40 µm in this zoom view.

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II. EXPERIMENTAL

A. Samples

In all cases, samples were fabricated on 0.35µm manufacturing technology, and were bumped with lead-free solder spheres having a pre-reflow diameter of 250µm. Silicon area was approximately 90mm^2 in all cases (~10mm x 9mm). These wafer-level-packages were mounted onto PCB substrates using vapour phase soldering, at a temperature of 234°C. The PCB substrates were fabricated using FR4 IS410 material (material parameters can readily be obtained from supplier data sheets), having 6 Cu metallization routing layers. These PCB substrates were 56mm x 42mm in area, with 1.6mm thickness.

In the case of bonded dice, bonding was performed at wafer-wafer level, using plasma-activated Si/SiO_2 direct bonding.

Three distinct cases were considered:

1) Thick monolithic dice: Die thickness ~725µm, no wafer bond, no TSVs. In total one such sample has been analysed, referred to as "sample 1"

2) Thin bonded dice: Total thickness ~280µm, no TSVs. In total two such samples have been analysed, referred to as "sample 2-a" and "sample 2-b".

3) Thin bonded dice with TSVs: Total thickness ~280µm, with TSVs. In total three such samples have been analysed, referred to as "sample 3-a" through "sample 3-c".

B. Topography and Deformation Measurement

The TDM equipment for Topography and Deformation Measurements under thermal stress conditions has been introduced previously [3]. Briefly, this system allows to apply virtually any thermal profile within the temperature range -60°C … +300°C with maximum heating and cooling rates up to +3°C/s and -6°C/s to electronic components and assemblies, and to simultaneously measure the sample's topography and deformation with a resolution down to the µm range.

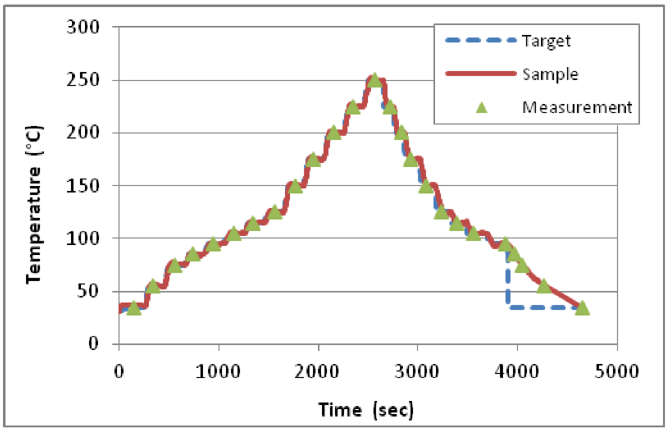

Fig. 2. Target temperature and measured temperature on the sample. The temperature is measured by a thermocouple, which is placed on the sample PCB at some mm distance only from the die.

In the present paper, the TDM system is used to assess the warpage of the upper one of two stacked dice, mounted on a small PCB (Fig. 1), for sample temperatures ranging from room temperature up to 250°C. The operated temperature profile and the measurement points for 3D topography acquisition are shown in Fig. 2. A rather slow temperature increase and decrease rate has been chosen, in order to keep the temperature of the entire sample as homogeneous as possible.

2D profiles along the two diagonals of the die are extracted from the complete 3D die topography, as shown in Fig. 3. The maximum of the amplitude of the two diagonals is considered as the die's warpage for a given temperature. This analysis is done at 25 temperatures within the total temperature range, both during heating up and cooling down of the sample.

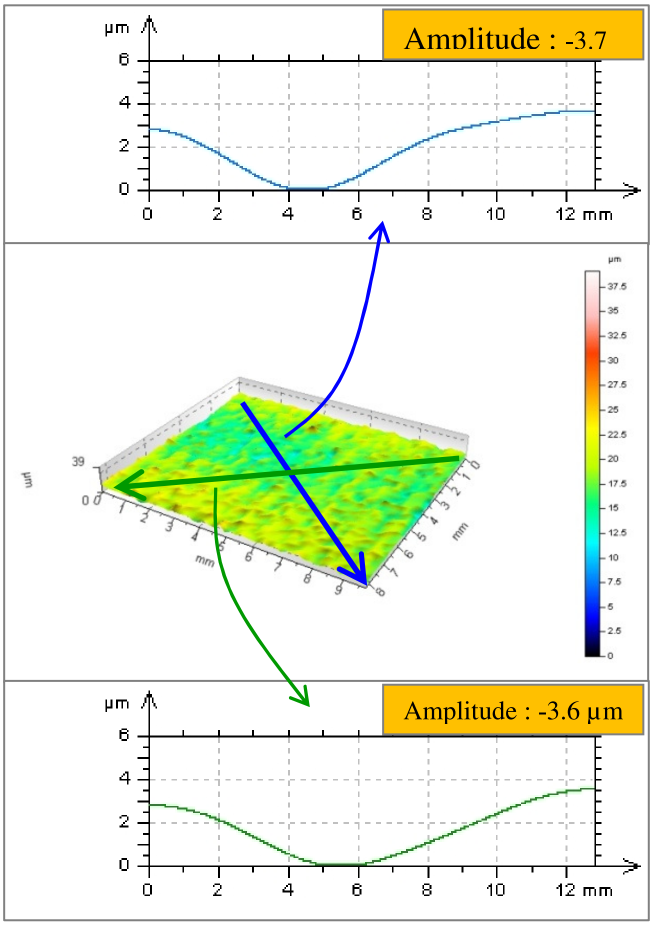

Fig. 3. Warpage measurement on the top die. The two diagonal 2D profiles are extracted, and their amplitudes are calculated. Amplitudes are marked with a negative (-) sign in case of concave profile shape, and with a positive (+) sign in case of convex profile shape.

C. FE Modeling

A 3D model of the sample has been simulated with FEM tool Comsol Multiphysics. The structure is supposed stress-free and perfectly flat at 27 °C, then thermal stress and related deformations are simulated in a temperature range of -50°C to +200 °C. Since real samples have some stresses already at room temperature, it is necessary to normalize the experimental results to the warpage at 25 °C, to compare them to the simulated results.

III. Results

A. Experimental Results

Figures 4-9 show the experimentally obtained warpages of all 6 samples, during heating and cooling.

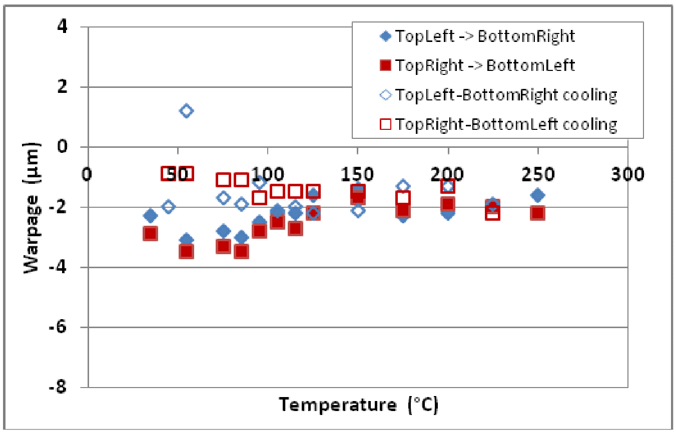

Fig. 4. Warpage measurement, sample 1

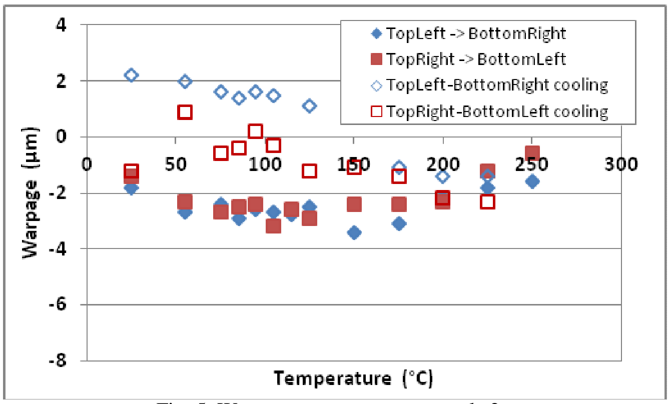

Fig. 5. Warpage measurement, sample 2-a

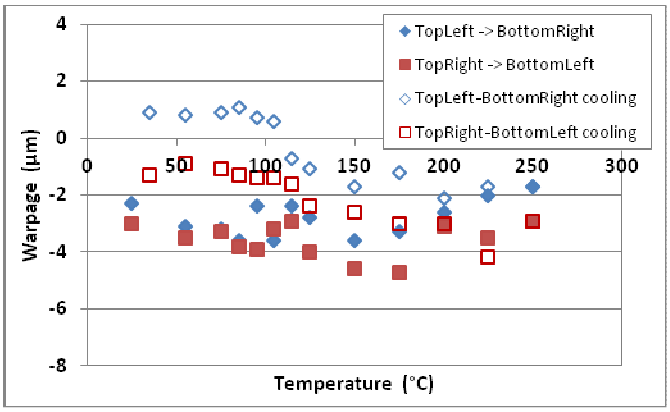

Fig. 6. Warpage measurement, sample 2-b

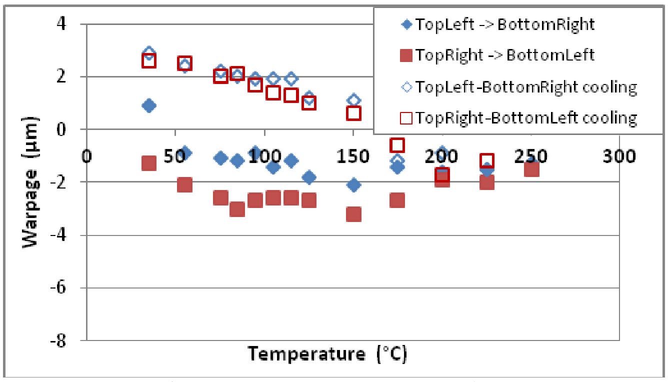

Fig. 7. Warpage measurement, sample 3-a

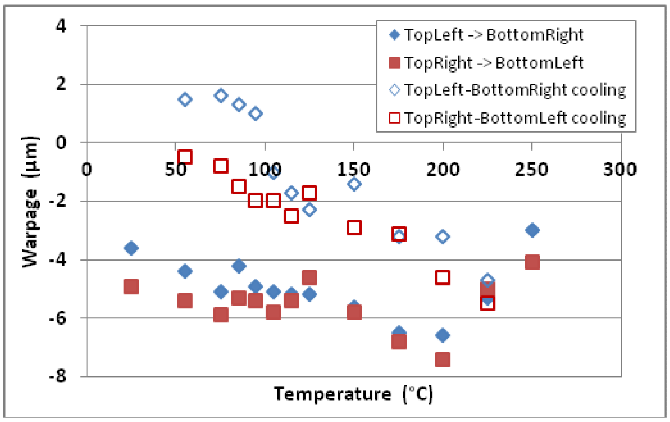

Fig. 8. Warpage measurement, sample 3-b

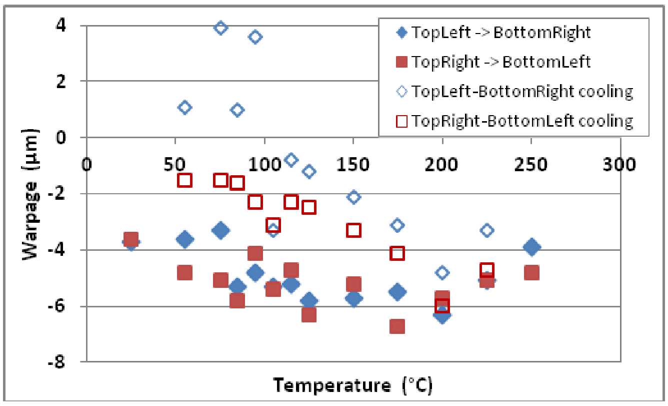

Fig. 9. Warpage measurement, sample 3-c

For each sample and each temperature, the two warpage values obtained respectively from the TopLeft-to-BottomRight and from the TopRight-to-BottomLeft diagonal over the die are indicated. A positive warpage value means that the shape of the 2D diagonal profile is convex, whereas a negative warpage value means that the shape of the 2D diagonal profile is concave.

Some general results are:

1. The measured warpage values are very small. Absolute values (disregarding the + or – sign), range from 0 to 7.5 µm.
2. For a given temperature, the warpage values extracted by the two different diagonals show good coincidence. There is no significant twist of the samples during the thermal profile.
3. All six samples are initially concave, and they stay concave during the entire heating period, up to 250°C.

Nevertheless, some differences appear in the warpage vs. temperature characteristics of the different types of samples:

1. Sample 1, the thick monolithic die, shows the lowest warpage variation over temperature of all analyzed samples. If we disregard the (noisy ?) -55°C value of the TopLeft-BottomRight diagonal, all other measured warpage values stay within a very small interval of -1 .. -3.5 µm.
2. Again, when disregarding the -55°C value of the TopLeft-BottomRight diagonal, sample 1 is the only one which stays concave during the entire temperature cycle, during heating and cooling. All other samples flatten out (i.e. warpage tends to 0) during cooling down, and even become more or less convex when approaching room temperature in the cooling down cycle.
3. In terms of deformation, the thick monolithic die is thus clearly the most "stable" configuration.
4. No significant difference is seen between the thin bonded dice with or without TSVs. In both cases, while heating up, the initially concave warpage tends to either stay constant or increase slightly further (sample becomes more concave). While cooling down again, all thin bonded samples flatten out, and even become slightly convex when approaching room temperature again.

B. Comparison Experimental Results – FE Modeling

The experimental results have been compared with a 3D FEM model for 2 cases: the thick monolithic die, and the thin bonded die with TSVs. The results are shown in Fig. 10 and 11. In the model, it is estimated that the internal stress of the components is 0 at 25°C, and increases with increasing temperature. By this way, a calculated relative deformation vs. temperature characteristics is obtained, which indicates a warpage value of 0 at 25°C initial temperature. Then, the calculated deformation vs. temperature characteristics is shifted by a fix warpage value in order to best reproduce the measured warpage vs. temperature curve during the heating phase.

It can be seen that in case of the thick monolithic die (Fig. 10) the model represents very well the measured warpage, during the entire temperature range, both during heating and cooling.

However, discrepancies are found between model and experiment in case of the bonded thin die with TSVs (Fig. 11). The main difference concerns the experimentally found differences of the warpage vs. temperature behavior during heating and cooling. If the coincidence between model and experiment is fairly well during heating, the cooling phase with its inversion of warpage (switch from concave to convex) can for evident reasons not be reproduced by a model which only takes into account a given temperature of a sample, but not its temperature history, to calculate the internal stress and thus the warpage.

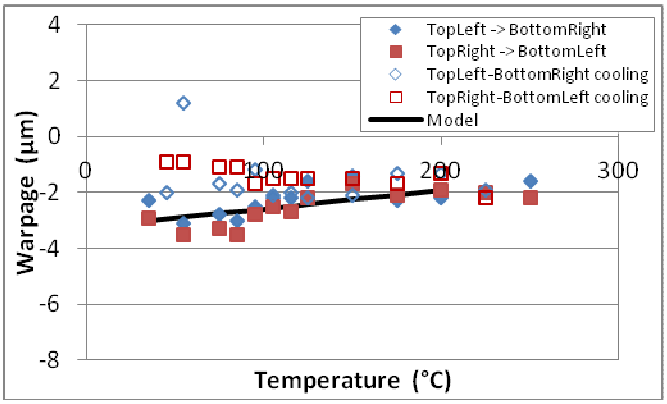

Fig. 10. Comparison of measured and calculated warpage in case of sample 1 (thick monolithic die).

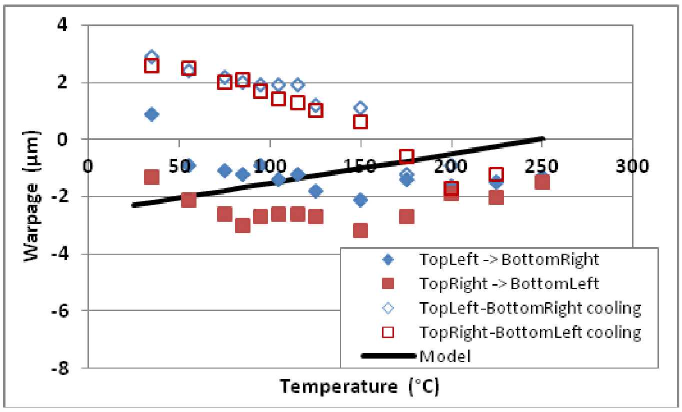

Fig. 11. Comparison of measured and calculated warpage in case of sample 3-a (thin bonded die with TSVs).

In fact, the reason of the shape switch in case of thin bonded dice is up to now well confirmed by all available measurements (Fig. 5 – 9), but not yet understood.

IV. SUMMARY

Warpage vs. temperature characteristics have been obtained both experimentally and by FE analysis, for different PCB-mounted stacked die configurations with or without TSVs.

Even if the measured warpage values are very small, the results are reproducible for several samples of the same or similar types of components. The experimental approach of warpage measurement even on such types of samples with very low warpage, and very low deformation with temperature, can be considered as validated.

During the heating phase, from 35°C to 200°C, the experimental results are in good coincidence with a 3D FEM model, especially in case if the thick monolithic dice.

However, further questions remain in case of the thin bonded dice: Here, the coincidence between model and experiment is quite fair during heating. During cooling, the shape flip from concave to convex cannot be reproduced by the model.

To further investigate the shape flip during cooling down, we plan to analyze in more detail the long term behavior of the samples after their cooling down to room temperature. Preliminary measurements show that the flip from concave to convex shape is not permanent, but that the sample comes back to its initial concave shape after 24-48 hours. It would be very interesting to better understand the dynamics of this process on the time scale.

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