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Direct Measurement of Silicon Strain in a Fine Pitch Flip Chip BGA Package

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Abstract
A method for directly measuring the silicon strain in a flip chip ball grid array (FCBGA) package is disclosed. The method uses anisotropically etched holes in the die backside to reveal fiducial crosses on the front side of the die. A geometric model is proposed that allows extraction of the strain component of the measured displacement. A finite element model is described which correctly predicts the sign and magnitude of the strain.

Key words
Bow, FCBGA, simulation, strain in silicon, warpage

I. Introduction

The strain in a silicon IC caused by the unmatched coefficients of thermal expansion (CTE) of the silicon and the package is a constant concern for packaging engineers. This strain is of increased importance in fine pitch FCBGA packaging because the short copper pillars have little compliance and absorb little strain. The strain in the silicon and the substrate tend to be larger in these packages.

One of the methods of characterizing silicon stresses relies on embedded stress sensors [1]-[3]. In this method, piezoresistive sensors are fabricated in the bulk silicon (Si) and the resistances of the sensors are monitored at various states of the flip-chip process. The piezoresistive coefficients of Si available in the literature can be used to convert the resistance measurements to silicon stresses [2]. When stress measurements are made over a range of temperatures, it is recommended to restrict this method to those stress states where the temperature coefficient of resistance (TCR) terms cancel out [1]. Another method involves measuring the lattice constant of silicon at various points on the backside of the die using Synchrotron X-rays. Since the lattice constant changes in response to residual stress, any change in the lattice constant can be used to estimate the out-of-plane strain in the die [4].

These methods indirectly measure the stress/strain in the silicon from the measurement on the die backside. To the best of our knowledge, the strain on the active side of the silicon has not been measured directly.

With the goal of directly measuring this strain, an experiment was devised to measure the relative positions of a pair of fiducials on the front side of the die, both before and after flip chip assembly. The ability of our mechanical modeling systems to predict the resulting strain was also tested.

II. Experimental

A. Experiment Description

Direct measurement of strains on the front side of the die is often not possible on assembled packages since the front side is encapsulated in assembly materials. To enable direct measurements, a silicon die was specially designed with fiducial markers on the front side of the die. The fiducials were defined on the first metal layer of the back end of line (BEOL) structure. Using the Bosch etch process, silicon vias were created on the backside of the die to allow measurement of fiducial positions using a high resolution optical microscope. A thin layer of silicon dioxide over the fiducials acted as an etch stop for the Bosch process. Optical images of the fiducials are shown in Figure 1. The wafers were thinned to 350 µm prior to the Bosch etch. The relevant die design features are summarized in Table 1.

Table 1 Die Attributes

Attribute	Value
Die x, mm	20
Die y, mm	10.4
Die thickness, mm	0.350
Cu pillar height/ solder height, µm	25/15
Bump pitch, µm	250

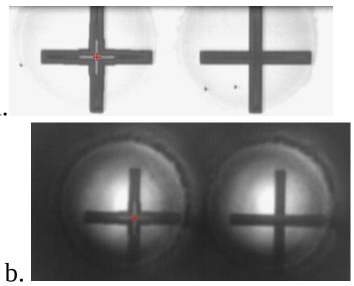
a.
b.


Figure 1 Optical microscope images of fiducials; a.) Front side, b.) Viewed from backside

The singulated die were assembled on a standard organic substrate using a thermal compression bonding with non-conductive paste (TCNCP) process. The substrate attributes are summarized in

Table 2. The die warpage on the assembly was measured using laser confocal microscopy and was found to be 27 µm from center to long short edge of the die.

Table 2 Substrate Attributes

Attribute	Value
Substrate x-y dimensions, mm	40 x 40
Layer count	7-2-7
Core thickness	400 µm
Core material	E705
Build-up Dielectric	GZ41
Pad Design	NSMD

The distance between the two front side fiducials was measured post assembly using a high resolution optical microscope. The algorithm built into the microscope locates the center of the fiducial from the average of several measurements. There is also built-in tilt compensation which relies on z-direction profiling near the feature to be measured. The resolution of the microscope is 200 nm.

B. *Experiment Results*

After assembly, four units were measured for fiducial spacing and bow. The bow was measured using a profilometer (Figure 2), which gave a value of about 20 µm, and using an interferometer (Figure 3), which gave a value of about 30 µm. The difference is because the profilometer being a line-scan device, and this makes it difficult to find the point of maximum deflection. The interferometer images the entire surface so the point of maximum deflection is easily identified. In the end, this difference is insignificant as will be discussed below.

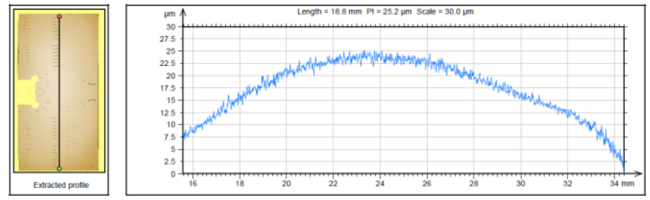


Figure 2 Profilometer scan of the ASIC backside

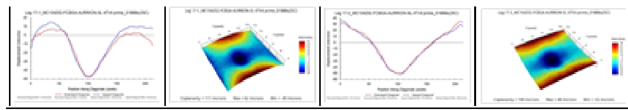


Figure 3 Shadow Moire' data for Units 1 and 2

High precision measurements of the die geometry were made using an automated confocal microscope with an accuracy of better than 100 nm. Before assembly, the distance between the fiducial crosses was the design value of 18.350 mm. After assembly, this value had decreased to 18.344 mm. Of course, when the die is bowed, the two sides will move closer together due to the geometric arrangement, but this is not strain. The challenge was to determine the portion of the decrease in distance that was due to bow. The remainder must then be the strain in the silicon. A geometric model was developed to calculate the bow geometry and estimate the strain.

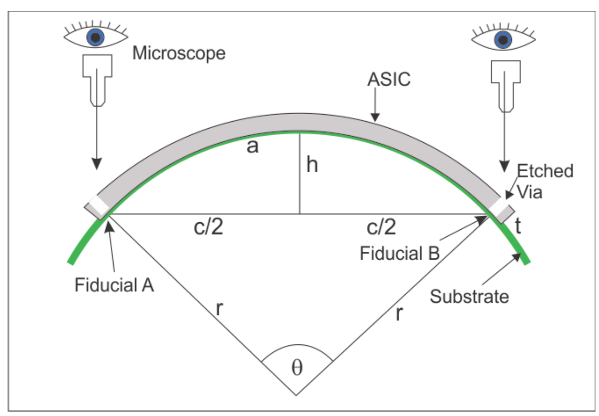


Figure 4 Geometric model of the bowed FCBGA package

Figure 4 shows the elements of the geometric model where ‘a’ is the arc length of the front surface of the die between the two fiducials, A and B. The radius of curvature is ‘r’ and the chord is shown as ‘c’, given an included angle of ‘θ’.

To determine the strain in the silicon, the arc length, ‘a’, between the fiducials must be calculated given the fiducial spacing, ‘c’, and the amount of deflection, ‘h’ (also known as the sagitta of the arc). The radius of curvature is given by:

$$r = \frac{h^2 + \left(\frac{c}{2}\right)^2}{2h} \tag{1}$$

The included angle can be found by:

$$\theta = sin^{-1}\frac{c}{2r} \tag{2}$$

Finally, the arc length can be found simply by:

$$a = r \cdot \theta \tag{3}$$

When these calculations are performed on the measured data, c = 18.344 mm and h = 20 µm, the following results are obtained:

$$r = 2103\ mm$$
$$\theta = 0.009\ rad$$
$$a = 18.3441\ mm$$

The calculations showed that 97% of the change in fiducial spacing was due to silicon strain of 0.03% and 3% was due to the geometry of a curve.

The large radius of curvature and small included angle indicate that the die does not have much bow for a die of this size. The arc length is nearly the same as the fiducial spacing, which means that virtually all the change in fiducial spacing is due to silicon strain. These equations can also be used to calculate the amount of bow needed to achieve the same fiducial spacing without strain in the silicon. If the silicon had infinite in-plane modulus and had zero strain, the sagitta would be 203 µm.

Another point worth mention is the insensitivity to the measurement of the deformation. Recalculation using h = 30 µm still yields a = 18.3441 mm. The difference is less than 100 nm which is within the measurement error.

III. Simulation

A. Model Description and Background

A 3D computer aided design (CAD) model of a simple die-on-substrate package was created to build a finite element analysis (FEA) model that could serve as a secondary calculation for experimental validation of strain measurement from fiducials on the die. The model was reduced to a quarter-symmetry model (made possible by the two planes of symmetry bisecting the die/package) to reduce simulation run time. The quarter symmetry model shown in Figure 5 is sufficient to represent the 10 mm x 20 mm die on a 40 mm x 40 mm, 14 trace layer substrate. It is noted that a 2D model along the longer symmetry plane of the die would also be a valid simulation method for the specific purpose of this model.

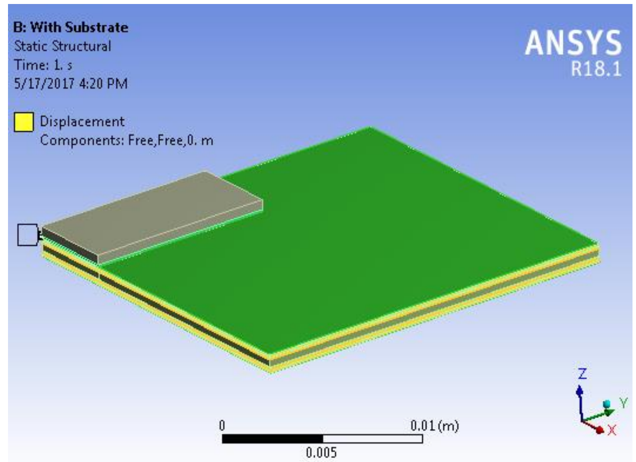


Figure 5 One quarter of the 10x20-mm die and 40x40-mm substrate package

ANSYS® Workbench Mechanical, Release 18.1 was used to perform the mechanical simulation. Linear-elastic material properties were applied to their respective bodies, the model was meshed as shown in Figure 6, and boundary conditions were applied. A combination of SOLID185 and SOLSH190 elements were used. The 3D Shell element SOLSH190 can allow for a higher element width to height ratio, which can create a more efficient model [5]. No contact elements were used in this model, since the mesh is fully connected between different bodies.

The bottom vertex of the die at the intersection of the symmetry planes (the center of the model) was given a fixed displacement constraint in the vertical direction while the faces along the symmetry planes were given a zero-displacement constraint in the direction normal to their respective symmetry planes. A body temperature condition was applied to the entire model to induce the desired model deformation due to CTE differences of the various materials in the model.

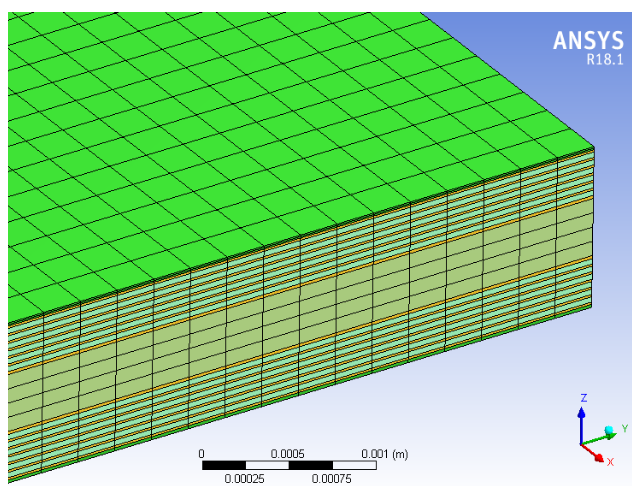


Figure 6 Close-up of Model Mesh showing substrate layers.

Copper in the substrate trace layers was assumed to be evenly distributed across each individual trace layer and each layer was assumed to have the same proportion of copper by area. This was done in the model by randomly assigning a percentage of elements within each trace layer to be copper; the remaining elements were left as either a dielectric material or a solder mask material. Copper coverage by trace layer area was assumed to be 74%. Table 3 summarizes relevant material properties used in the model.

Table 3 Material properties used in simulation.

	Elastic Modulus ($< T_g$) ($> T_g$) MPa	Glass Transition Temp (T_g) °C	CTE1 ($< T_g$) CTE2 ($> T_g$) mm^{-6}/mm
Die (Silicon, <100>) [6]	130,000	-	2.6
Trace Metal (Copper)	128,700	-	17
Substrate Core (E-705G) [7]	28,000	-	5.5
Substrate Build-Up Dielectric	7,500	158	23 78
Substrate Solder Mask	900 60	125	50 110
Underfill/Die Attach	8,000 2,000	130	26 130

The resulting measurement point in the model corresponded to the location of one of the fiducial points in the experimental setup; this one measurement point serves as both fiducials in the FEA model due to the symmetry condition. Point 1 in Figure 7 is at (0,0,0), and Point 2 is at (0,9.175,0), where coordinates are in mm. The distance between the two fiducials in the experiment package was 18.35 mm.

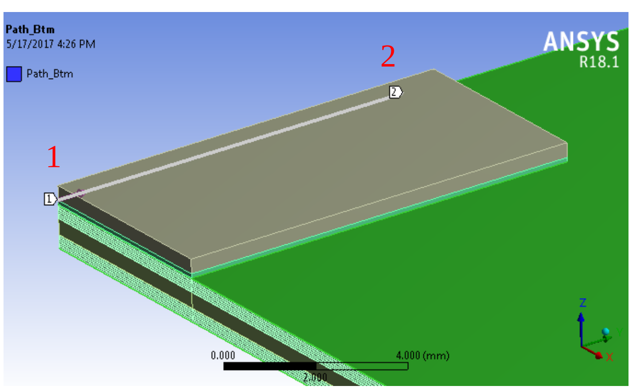


Figure 7 Path object in ANSYS Mechanical from 1 (fixed-point) to 2 (measurement-point). Note that the path lies along the long symmetry plane, and point 2 corresponds to a fiducial location in the experiment.

Two simulation load steps were required by the model to match the two states of the die (before die-substrate attach, and after) when the fiducials were originally measured. Both measurements were made at room temperature in the real-world experiment. To capture this within the model, the silicon die was defined to have zero thermal strain at 22°C (the initial and final fiducial measurement temperature). For the first load step, the substrate and die attach adhesive were deactivated (using ANSYS command *EKILL*, which temporarily defines an element's stiffness as virtually zero [8]), and the die was warmed from room temperature to a high temperature. Because the substrate and die attach were not active, the die remained undeflected.

The second load step revived the substrate and die attach elements (using ANSYS command *EALIVE*, which resets an element's stiffness to its material definition and erases any mechanical strain history of that element, defining elastic strain and stress to be zero upon the element's resurrection [8]). This allows the entire package to be at a zero-elastic strain state at the high temperature, while preserving the information of the silicon die's initial shape and size at room temperature. This second load step cooled the package model back to 22°C.

Measurement of the vertical (Z direction) deformation, horizontal (Y direction, along the line created by the two fiducial points) deformation, and horizontal elastic strain along the path were made.

The model was calibrated to match the vertical deflection between the two fiducials as measured on the real-world package: 0.0325 mm. This calibration was done by adjusting the high temperature at which the die was attached to the substrate in the simulation model. This was a brief trial-and-error process to calibrate this model. Note that calibration is necessary to limit the contribution of error sources such as simplified material properties and various assumptions made during modeling. The high temperature (zero mechanical stress temperature) of this model was 104.1°C.

The simulation result was found to be insensitive to model mesh size and count. This confirms that the model was sufficiently designed to generate accurate results.

B. Model Results

Because the simulation model was calibrated to the real-world measurements of the experiment package, it is expected that the vertical deflection plot and vertical deflection position of the model fiducial point match those measurements.

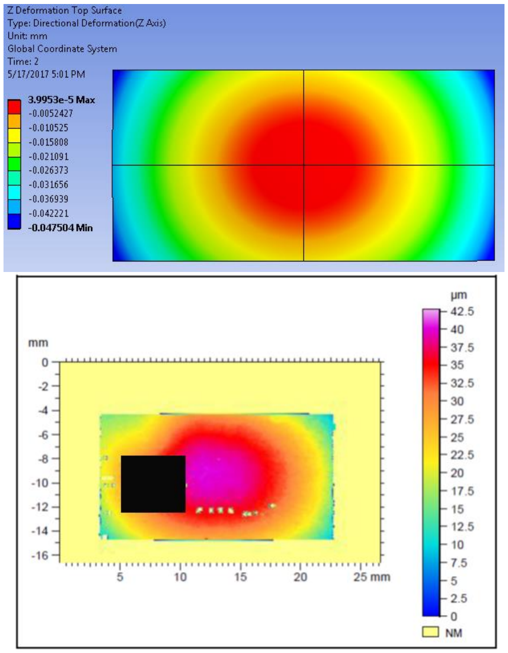


Figure 8 Simulation vertical deflection plot on the top surface of the die (top), and experiment measurement plot (bottom).

The more interesting and useful data generated from simulation is the horizontal deflection and along-path strain. Vertical deflection of Point 2 (Figure 7) in the model was -0.03247 mm; restated to remove the negative sign, the center of the die was 0.03247 mm above Point 2. This corresponds to the arc height in the experiment.

Horizontal deflection of Point 2 in the model was -0.00300 mm (0.00300 mm toward the center of the die); restated to account for the symmetry plane, Point 2 and its imaginary opposite on the other side of the symmetry plane (both representing the fiducials in the experiment die) deflected closer to each other by .00600 mm. The horizontal distance between the two points was reduced from 18.3500 mm to 18.3440 mm. This corresponds to the chord length in the experiment.

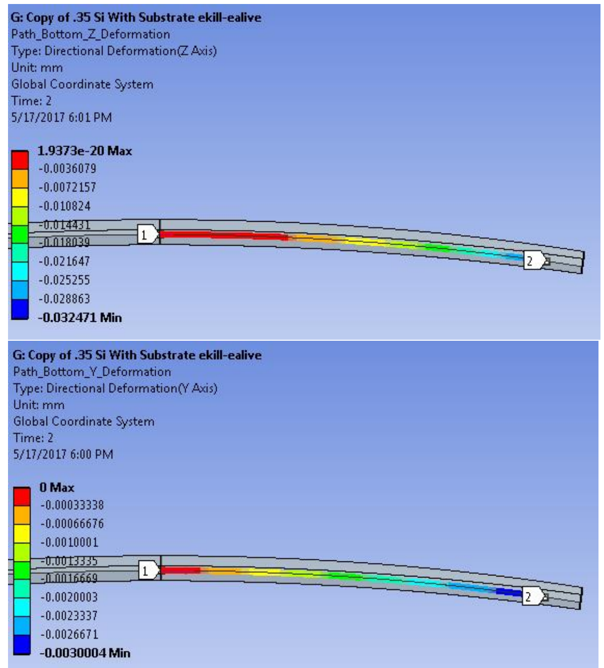


Figure 9 Vertical deflection along path (top), Point 2 deflects 0.03247 mm in the negative Z direction; Horizontal deflection along path (bottom), Point 2 deflects 0.00300 mm in negative Y direction.

An equivalent measurement in the simulation model to calculated strain in the real-world experiment cannot be made at a single point, since measuring the change in the distance between the two fiducials in the experiment package and basing a strain calculation on that measurement will result in an averaged strain value across that entire distance. Because of this, the direct strain measurement from simulation should be performed as an average across all points along the path between the two fiducials.

The Figure 10 shows the resulting strain along the result path. The resulting average strain from the path was negative 3.18 x 10^{-4} mm/mm (negative strain is compressive strain). Equations (1-3) allow the arc length between the fiducials (Point 2 and its symmetric counterpart) in the simulation model to be calculated. The 0.003247 mm arc height and 18.34400 mm chord length result in an arc length of 18.34415 mm.

The overall distance along the surface of the die between the two simulation fiducials was therefore reduced by 0.00585 mm from its original distance of 18.350 mm. The average strain along that surface was then calculated to be -0.00585 mm per 18.350 mm, which is -0.00032 mm/mm (or 0.032%).

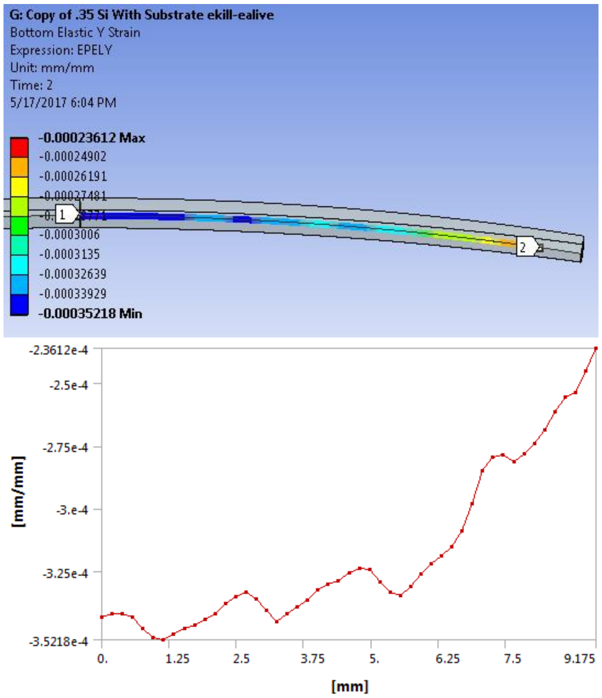


Figure 10 Resulting strain along the path in graphical (top) and plotted (bottom) forms. Variations in the slope are due to variations in the copper concentration in the trace layers beneath that point in the package.

These numbers match well with and validate the calculated strain on the bottom surface of the die in the experiment package.

III. Conclusion

Direct measurement of strain on the front side of the silicon post die-attach has been reported for the first time. This was accomplished by observing a pair of fiducials on the front side of the die through a silicon via etched on the backside of the die. The strain on the front was estimated to be 0.03%. A thermomechanical model was then created and calibrated to the direct measurements. The averaged strain result at the surface of the silicon in the FEA model between the two equivalent fiducial points was 0.032%. The close agreement of these results supports the hypothesis that the change in position of one fiducial relative to another fiducial after die attach provides a basis for direct measurement of strain on the front side of a silicon die.

A potential application for this measurement would be characterizing the silicon strain for sensitive circuitry during package prototyping stages. For any geometry-sensitive structure (e.g., oscillators for clocks or frequency generators), this measurement technique could help package designers address error contributions due to factors introduced during package manufacturing.

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