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THINNING AND POLISHING HIGHLY WARPED DIE: PART II

A DISCUSSION OF THE MECHANICAL LIMITATIONS OF FLATTENING A CURVED DIE IN PREPARATION FOR DIE THINNING

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INTRODUCTION

In the August 2015 issue of *EDFA* magazine, the use of thickness measurements to adjust the processing profile used to thin and polish a curved or warped die was discussed. Here the mechanical, physical, and mounting variables of the thinning and polishing process are discussed, with particular attention to the mounting processes and their effects on the process results.

DIE CURVATURE

Packaged dice are invariably warped within the package as a result of a number of variables. There is a general belief that forcing a die-package system temporally to near flat "relaxes" the system, and thus, one will obtain better results from thinning processes.

The fundamental problem with integrated circuit packaging is that the final package combination is always warped. Small dice warp less than large dice simply because they are small. Prior to packaging, dice are very flat. Such curvature is created during the packaging of the dice. The attachment of a flip-chip to its substrate involves the high-temperature reflow of the C4 balls. Overmolding a die on a leadframe is generally done by molding processes where the molding compound is heated to rather high temperatures prior to injection around the die and leadframe. As components cool down from the processing temperature, the differences in the thermal expansion coefficients of the bonded materials generate stresses that result in the curvature of the die surface. Materials are generally selected to have nearly the same thermal expansion, but the match is never exact. One or two parts per million in the thermal coefficients makes a big difference in the resulting flatness of a die.

The standard flip-chip with a single die on a single package substrate is the easiest system to describe. Two materials with different thermal expansion characteristics that are bonded together will demonstrate curvature at any temperature other than the temperature at which the components were bonded. Because the stress induced by the difference in thermal expansion is uniform across the interface between the two materials, the shape of the interface is nearly spherical. The curvature of two bonded dissimilar materials has been described and is well known to change linearly with change in temperature.[1]

In a flip-chip package, the die and substrate are flat before being heated to bonding temperature. The chip-substrate combination is then cooled after reflow, and the reference temperature, the temperature where the curvature = 0, is reached at the *solidus* temperature of the C4 balls. After a plastic encapsulated die is exposed by removing the backside encapsulant and die-attach metal pad, its curvature can be described as above, with the characteristics of the frontside encapsulant replacing the characteristics of the package substrate.

The curvature of the die is not affected by die size, only thickness. If the die dimensions are small, the curvature results in a proportionately smaller difference in surface height across the die surface. Small (less than 5 mm^2) dice may not have surface height differences that require any special considerations. Typical surface profiles show less than a 0.005 mm height difference for a 5 mm^2 die, while a 20 mm^2 die may show as much as 0.090 mm. Curvature is not a real concern on small dice because of the smaller height difference resulting from a smaller section of a sphere. The radius of the sphere is fixed by die thickness, temperature, and material parameters.

Because the die and package components are not the same size, the standard calculation for curvature is only an approximation, but it gives a good basis for calculating the stresses on the die. The stresses the die is subjected to are equal and opposite of the stresses in the substrate. The stresses cause an elastic deformation of the interface of the die, making the interface surface smaller than the die's unmounted dimensions. This elastic deformation causes the die to curve and the free surface of the die to be larger than the unmounted die dimension. The interface is stressed in compression and the free die surface in tension. The stress is vertically distributed about the plane at the center of the die thickness, as shown in Fig 1. The actual stress at the surfaces can be determined by measuring the height of the die free surface at the die center and at two points equidistant from the die center. The radius of the free surface is:

$$R_F = ((2 \cdot X)^2 + 4 \cdot (H_C - (H_1 + H_2)/2)^2)/8 \cdot (H_C - (H_1 + H_2)/2)$$

where R_F is the free side radius, H_C is the measured die center height, H_1 is the height at X distance from the die center, and H_2 is the height at $-X$ distance from the die center.

The stress in the surface fiber is as follows. (The equations and concepts in this article are generally accepted as valid and are taught in all strength-of-materials classes.)

$$S = E \cdot (1 - (2 \cdot R_F/(2 \cdot R_F - T)))$$

where S is the stress at the die free surface, E is Young's modulus of silicon, and T is the die thickness. The Young's modulus of silicon is dependent on the crystal orientation, with a value of approximately 190 GPa for forces in the plane of a (100) wafer.[2]

The equivalent bending moment on the die is a function of its thickness, width, and Young's modulus. From the standard equation, $1/R = M/E \cdot I$, the moment can be calculated:

$$1/R_F = M/(E \cdot W \cdot T^3/12)$$

$$M = E \cdot W \cdot T^3/(12 \cdot R_F)$$

where R_F is the free side radius (in meters), E is Young's modulus of silicon, W is the die width (in meters), and T is the die thickness (in meters).

AN ACTUAL DIE

A typical 19.699 mm × 16.089 mm die characterized for die surface profile is shown leveled in Fig. 2. The die was 0.770 mm thick, and the die center was 0.041 mm above the heights measured 7.879 mm from the die center in the 19.699 mm direction and 0.031 mm above heights measured 6.435 mm from the die center in the 16.089 mm direction. The average free surface radius is approximately 0.713 m. The maximum stress in the die is 65.68 MPa, and the moment is 0.1047 NM, or approximately 1061.2 g-cm. (The moment is present on all die edges as required to create a near-spherical surface.) This equivalent moment is applied to all die edges and is counteracted by equal and opposite moments on the substrate. (The sum of all forces in any system must equal zero. If not, the system will have to move in response to the nonzero forces. That is, it would move across the desk on its own.)

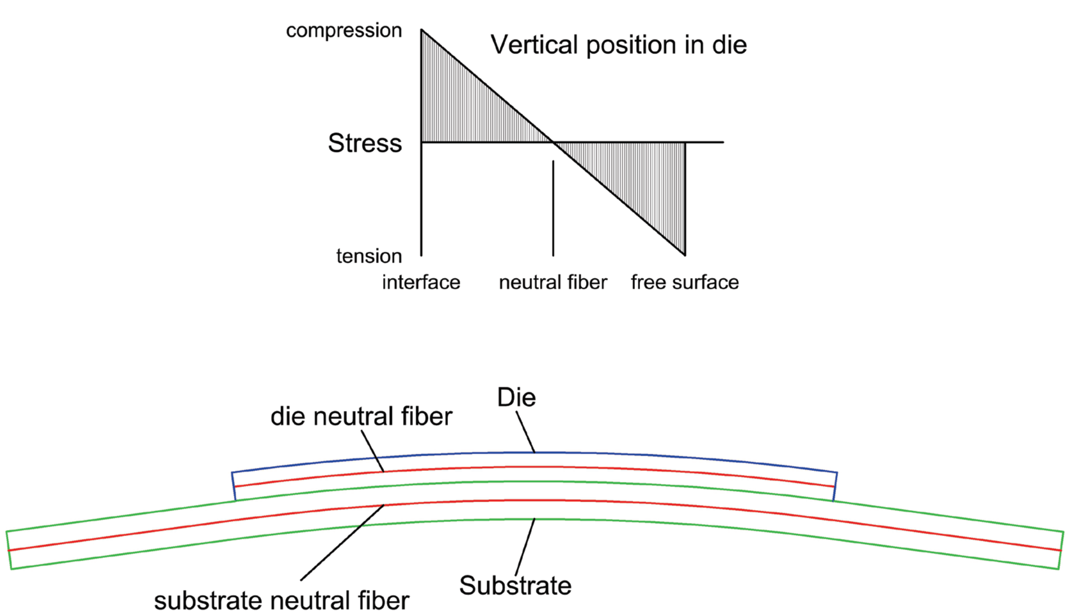

Fig. 1 **Distribution of stresses over a die-package substrate mechanical system**

All of the above assume that the die and substrate are homogeneous and infinite. This is not the case because the die and substrate have fixed dimensions; the trace density in the substrate varies, as does the different functional layers on the die surface. The C4 balls may not be evenly distributed over the interface and may not be exactly the same diameter. Note that the curvature is significantly different in the long and short direction of the die. In addition, the variables along the interface plane will cause locally different curvatures and stresses. The average curvature and stress may come close to the above described, but local variations will exist and can be significant. The above actual die was analyzed for local curvature variations. Although low dimensional curvature calculations are difficult due to the profile measurement uncertainty, some local curvature deviations can be observed. Table 1 shows calculated curvatures based on the measured profile data. Table 2 shows the difference for each curvature calculation and the mean divided by the standard deviation. Any number 2.0 or greater can be assumed to indicate a significant local deviation in curvature. There are three points (shown in red) that are two sigma or more difference from the mean curvature.

ATTEMPTS TO FLATTEN DIE

There are several ways to attempt to flatten the die surface. A common method is to generate a vertical force on the die surface that is sufficient to bring the die-package system to a near-flat state. This requires a force that counteracts the moment on the die edges. Going back to the above real die, a weight in excess of 5 kg would be required to bring the 19.765 mm × 16.056 mm die to a near flat. The die-package system is then bonded to a sample holder with a material that is assumed to stabilize the entire die-substrate-holder system.

Another method is to create a thermal gradient across the die-package system that thermally expands the package while keeping the die from expanding. Given the relationship between curvature and temperature, the only way the die-substrate system can be flattened thermally, other than by heating to the attachment temperature, is by effectively heating the substrate and cooling the die. Because the die surface is subject to both radiative and convective heat losses, heating the system from the substrate side can create a significant temperature gradient. This transient "flat" state is then bonded to a sample holder, again with a material that is assumed to stabilize the transient "flat" thermal state. The success of the process is generally determined by mechanical gauge measurements on the die surface. A good operator can, by either method, force a die surface to measure fairly flat immediately after mounting.

Normal wax mounting de facto creates a thermal gradient, with the package/substrate hotter than the

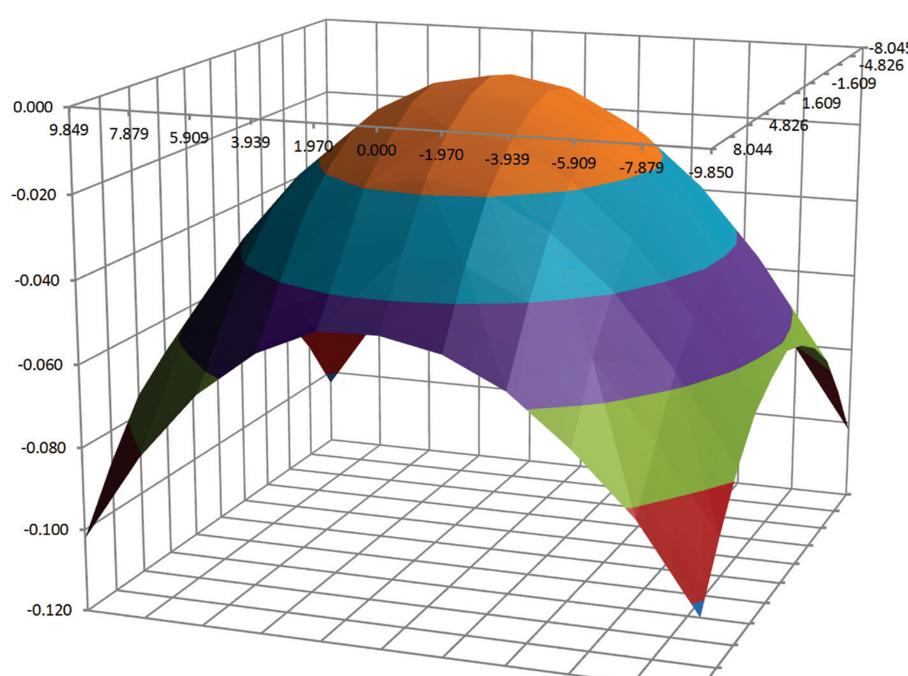

Fig. 2 **Measured wire frame representation of the free die surface with planar rotation removed. The die was mounted on a holding fixture that had the area under the die relieved. The relieved area is 2 mm beyond the die edges to prevent the holding fixture from interfering with the process tests. The device was waxed on the edges only, allowing the relieved area to float free.**

Table 1 Point-by-point curvature calculated using the second point in both *X* and *Y* away from the central calculation point. The *X*- and *Y*-direction calculations were averaged to obtain the indicated point curvature.

Y-distance from center	*X*-distance from center 9.849	7.879	5.909	3.939	1.970	0.000	−1.970	−3.939	−5.909	−7.879	−9.850
8.044	…	…	…	…	…	…	…	…	…	…	…
6.435	…	…	…	…	…	…	…	…	…	…	…
4.826	…	…	858.23	805.9	788.92	739.15	731.69	745.97	783.89	…	…
3.218	…	…	740.39	823.66	826.88	720.03	730.05	763.71	850.09	…	…
1.609	…	…	788.94	777.58	772.68	736.01	742.19	786.57	770.52	…	…
0.000	…	…	782.12	691.96	691.81	711.57	732.58	712.55	731.35	…	…
−1.609	…	…	757.12	760.84	726.18	727.83	725.11	746.97	769.02	…	…
−3.217	…	…	753.78	803.3	791.74	711.56	686.79	786.56	831.22	…	…
−4.826	…	…	757.13	858.24	726.19	712.56	801.47	753.8	855.71	…	…
−6.435	…	…	…	…	…	…	…	…	…	…	…
−8.045	…	…	…	…	…	…	…	…	…	…	…

Average: 747.5 **Standard deviation: 44.888**

Table 2 Difference from each point in Table 1 to the mean curvature divided by the standard deviation. The absolute value indicates the significance of the deviation from the mean value. A value of 2.0 is two sigma variation.

Y-distance from center	*X*-distance from center 9.849	7.879	5.909	3.939	1.970	0.000	−1.970	−3.939	−5.909	−7.879	−9.850
8.044	…	…	…	…	…	…	…	…	…	…	…
6.435	…	…	…	…	…	…	…	…	…	…	…
4.826	…	…	2.5	1.3	0.9	−0.2	−0.4	0.0	0.8	…	…
3.218	…	…	−0.2	1.7	1.8	−0.6	−0.4	0.4	2.3	…	…
1.609	…	…	0.9	0.7	0.6	−0.3	−0.1	0.9	0.5	…	…
0.000	…	…	0.8	−1.2	−1.2	−0.8	−0.3	−0.8	−0.4	…	…
−1.609	…	…	0.2	0.3	−0.5	−0.4	−0.5	0.0	0.5	…	…
−3.217	…	…	0.1	1.2	1.0	−0.8	−1.4	0.9	1.9	…	…
−4.826	…	…	0.2	2.5	−0.5	−0.8	1.2	0.1	2.4	…	…
−6.435	…	…	…	…	…	…	…	…	…	…	…
−8.045	…	…	…	…	…	…	…	…	…	…	…

die. The die is fully exposed to the environment, allowing both radiative and conductive thermal losses, while the package/substrate is at least partially isolated by the die itself and in closer proximity to the source of heat. The length of time that the device is left at temperature will determine the final gradient. Rapid processing will result in greater gradients, while long soak times will produce smaller thermal differences. A device cannot be mounted in a free state, but insulating the device from the environment and long soak times will get the die closer to a free state. The actual die above was characterized for incidental flattening from wax mounting, with the resultant profile shown in Fig. 3. The *X* and *Y* center profiles are included in Fig. 4.

The applied force method was evaluated by repeatedly remounting a device with different forces applied to

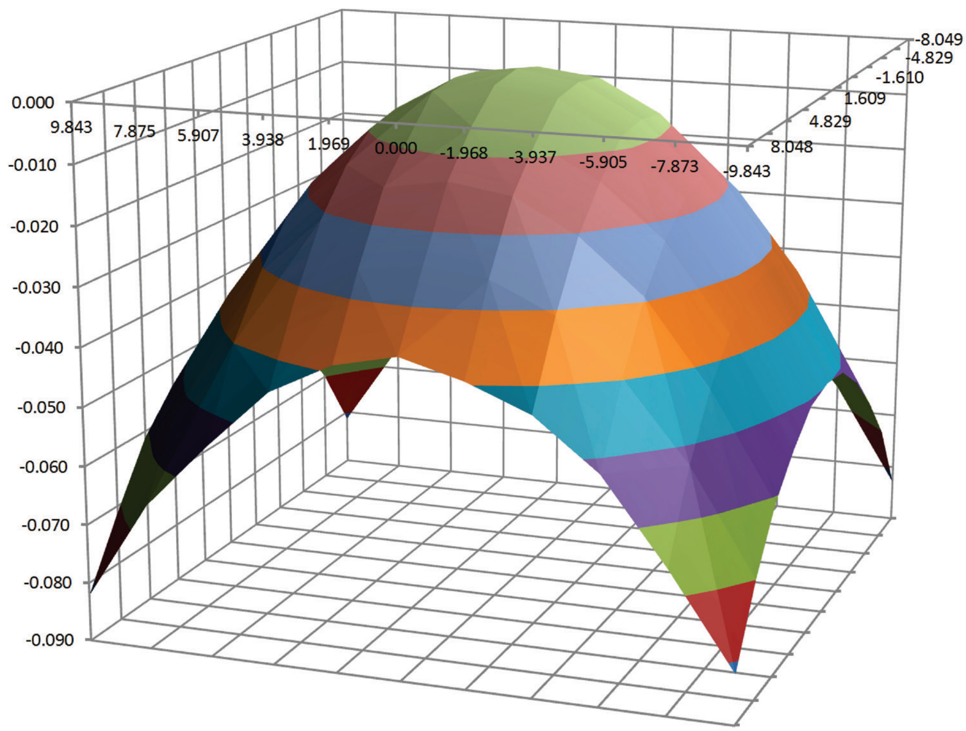

Fig. 3 **Profile of the die of Fig. 2 with the entire substrate surface in contact with the mounting wax. The difference between Fig. 2 and 3 shows the profile variation resulting from a careful mounting process. Planar sample rotation has been removed. The die was mounted on the previously described holding fixture. The relief area was filled with mounting wax, and enough time was allowed at mount temperature (5 min) for excess wax to flow out of the relief area, reducing hydrostatic alteration of the mounted die surface. The device was covered with a sheet of ¼-in.-thick polyethylene foam to isolate it from the environment. The only deformational forces involved are those created by the thermal gradient from the mounting fixture to the die face.**

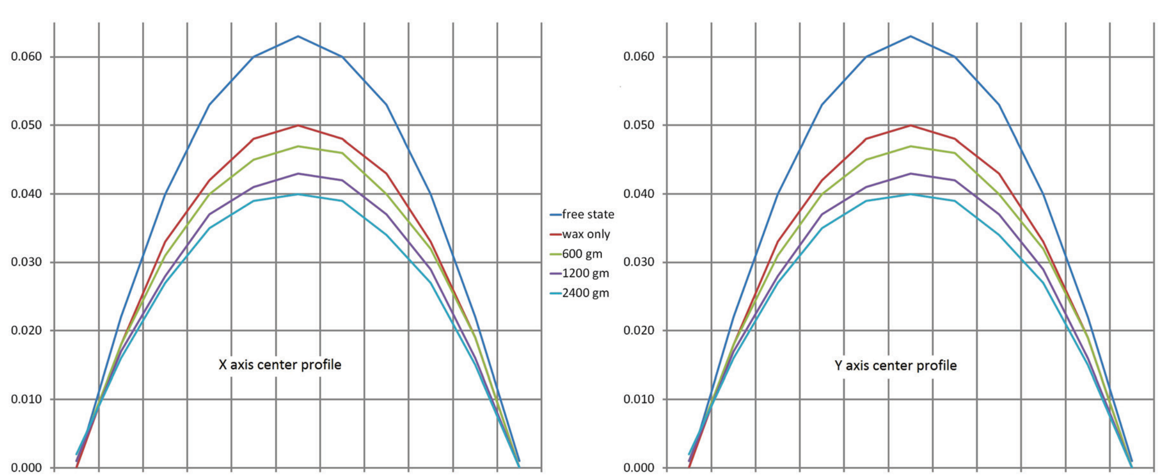

Fig. 4 **Die profile changes across the *X*- and *Y*-axis centers created by applied force during wax mounting. This clearly shows that wax mounting creates significant force.**

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 (continued from page 8)

the die center and, after cooling, measuring the surface profile. The test setup is shown in Fig. 5 and the measured profiles results in Fig. 4.

RESULTANT FORCES

The forcing of a die to relative flatness does not relax anything. It increases the stresses in the die-substrate combination and generates significant forces on the mounting medium. In an equilibrated state, the forces that create die curvature are distributed vertically through the die and substrate thickness. All the bending moments on the die and substrate cancel. Forcing the die to a nearly flat state redistributes the stresses on both the die and substrate. The sum of all the forces must equal zero. Adding a vertical force to make the die flatter must increase the forces in the die-substrate system in ways that equal the added vertical force. When flattening is done thermally, the resultant forces, after thermal equilibration, are the same as if the flattening force was from a weight. The same die-substrate flexure requires the same force. Thermal flattening simply uses a thermal gradient to generate the equivalent downforce instead of using a heavy weight.

The forcing of a die to present a flat surface alters the distribution of forces, resulting in near-zero stress in the free die surface and a doubling of the stress at the die-substrate interface. In extreme cases, this increase in stress can bring the die close to fracture failure. When an overstressed die is processed, the process forces add to the resident stresses in the die. If the sum exceeds the fracture limit, the die will fail with the primary fracture surface being a series of conchoidal breaks more or less parallel to the die-substrate interface. This failure is generally referred to as delamination, as shown in Fig. 6. The bulk silicon has well-defined tension and compression limits.[2] Exceeding either will result in catastrophic die failure.

MOUNTING FORCES

The forces generated by making a die flat translate into forces directly on the mounting medium. Typically, the mounting medium is a relatively low-temperature wax. The wax is not truly solid and can be viewed as a very viscous liquid that will move due to any applied forces. The movement is slow and more or less a linear function of applied force. CrystalBond 509 (Aremco, Valley Cottage, NY) was evaluated for flow over time with applied force for the tensile forces caused during mounting. With a ball-grid array or flat substrate, the mounting medium is stressed primarily in tension, while the pin-grid array (PGA) package stresses are much more complex and variable, resulting in both tensile and shear forces.

A device without pins or balls attached to the substrate was mounted with force applied to flatten by the mechanism in Fig. 5. The profile was then measured at different time intervals to determine the rate and magnitude of profile change. The test results are shown in Fig. 7. In addition, a PGA reference part was mounted with the same force applied to the center of the die to flatten the die. The die was then profiled at different time intervals to record the change. The test results in Fig. 8 clearly show faster movement. The die surface movement is difficult to numerically relate to the forces involved in die flattening and thinning due to variations in mounting parameters, but limit cases can be easily envisioned. A die-substrate system mounted in a state of thermal equilibrium will exert no force on the mounting medium. A device forced flat will exert the full flattening force on the mounting medium. That is, if it takes a 5 kg weight to force the die-substrate flat, the 5 kg force will be applied directly to the mounting medium.

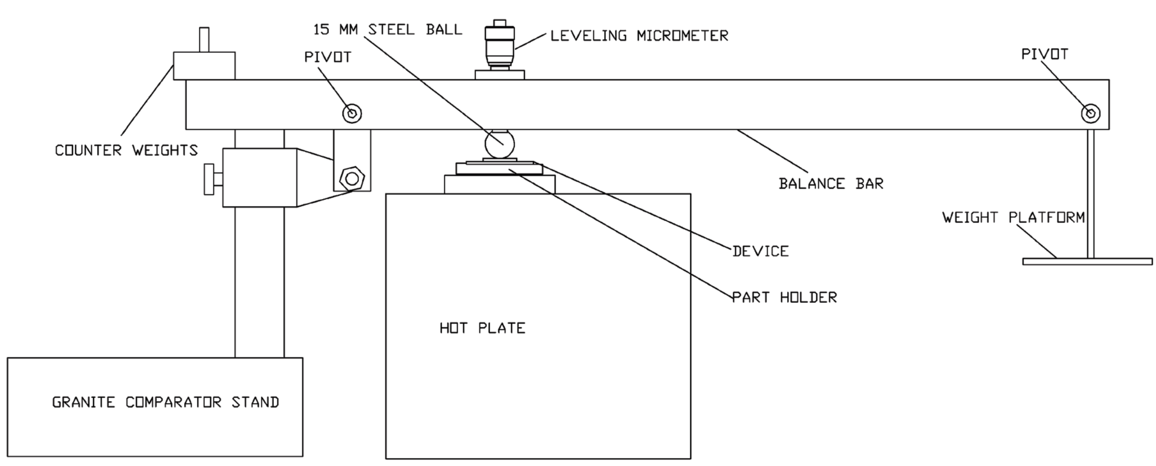

Fig. 5 **Fixture used to apply a known flattening force to test samples**

FORCE CHANGES DURING THINNING PROCESSES

As the die is thinned, the distribution of forces changes. Before any thinning, the stresses at the die-substrate interface are resisted by the full thickness of the die. As silicon is removed, there is less resistance to the forces and, in an unmounted state, the curvature of the die surface will significantly increase. The reduced resistance to the bending stress will increase the force on the mounting medium. The increased force on the mounting will proportionally increase the flow rate, resulting in the shape of the die surface changing during the thinning process. With devices, similar to the reference device above, that were mounted in a free state, the center of the die will rise due to flow of the mounting medium by more than 0.020 mm. This change in surface profile occurs during a 45-min-long rough grinding process that removes 0.625 mm of silicon from the free die surface. Forcing the device flat during mounting will more than double the changes in the surface profile. This will make the die center, after grinding, more than 0.040 mm thinner than the die edges. In extreme cases, the center of the die will be removed entirely while leaving the edges rather thick.

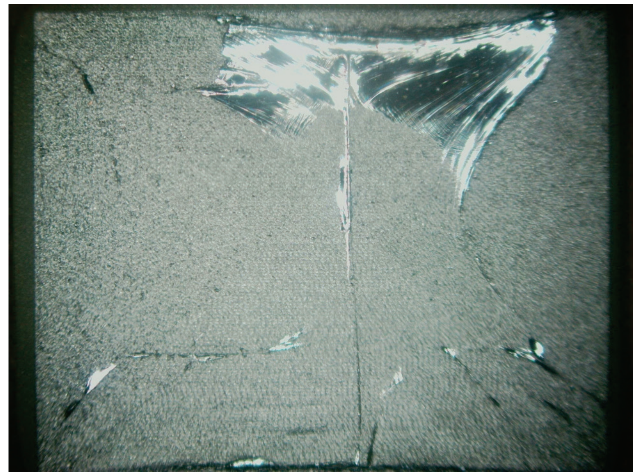

Fig. 6 **Mechanical failure of a die subject to excessive horizontal stresses. Note that the fractures are not aligned to any crystal plane but are conchoidal in form and generally in the plane of the applied stresses.**

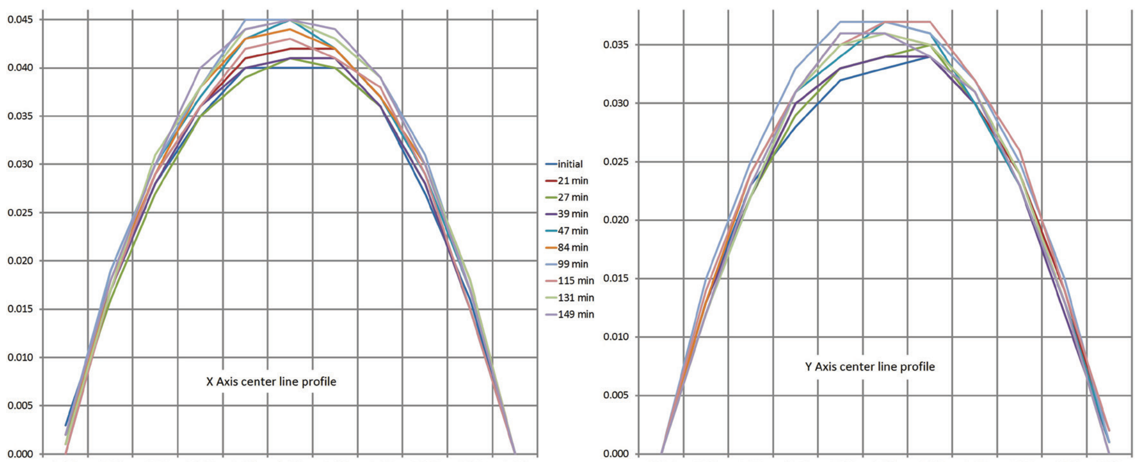

Fig. 7 **Time-variant changes in surface profile across the *X*- and *Y*-axis center lines of a mechanically flattened sample without solder balls or pins attached to the package/substrate. The device was treated as described in Fig. 3.**

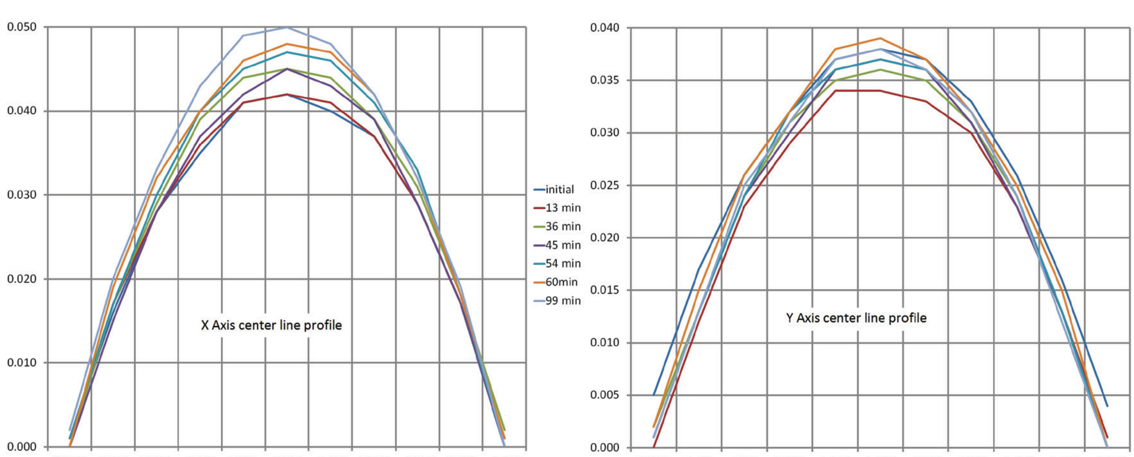

Fig. 8 **Time-variant changes in surface profile across the *X*- and *Y*-axis center lines of a mechanically flattened PGA sample**

CONCLUSIONS

A device mounted in a near-free state will change in profile during die thinning due to the flow of the mounting medium and the changes in force distribution. A device that has the die surface forced to be flat will exert the flattening force on the mounting medium, forcing a greater flow of the medium during processing. These flattening forces add to the forces applied as a result of thinning the die during processing. The sum of forces may be many times greater than the forces exerted on the mounting medium by a near-free-state mounted device and will increase surface profile changes proportionally.

The force required to flatten a device significantly increases the stresses in the bulk silicon. These stresses added to the stresses caused by processing forces may exceed the fracture limit of the bulk silicon, causing the die to "delaminate." Forcing the die surface to be flat by any means increases the chance of total die destruction and significantly increases the profile changes during processing time, resulting in large endpoint thickness variations.

The best way to mount a device for die thinning is in a near-free state. This applies only the forces resulting from thinning the die to the mounting medium. Care must be taken to thermally isolate the device, sample holder, and mounting medium from the environment to prevent the incidental creation of a thermal gradient across the device. It also requires long "soak," or thermal equilibration, times. An alternative is to "age" the device after mounting. Allowing a few hours between mounting and processing lets the wax flow from the mounting stresses and the device to assume a profile that is closer to its free state.

Mechanically clamping the sample allows the unclamped portion (most of the sample) to move without restriction to the redistribution of forces stemming from the thinning process, resulting in the fastest and least controllable changes in the sample surface profile. In addition, the clamping forces produce their own bending moments that add to the forces built in by packaging the sample's die.

A "free-state" mounted part will have to be thinned using a tool that can follow the surface profile. The die profile will change during processing, but the changes will be less compared to a die that is forced, by any means, to a flat profile and thinned by a tool that operates in a fixed plane.

Because there are significant local variations in surface curvature as a result of nonhomogeneous component distributions in the die, substrate, and C4 balls, attempts to approximate the die surface as spherical may not be effective. Variations in surface curvature and changes in curvature during the thinning process will result in the actual surface never matching the theoretical sphere. These local variations can be clearly seen in Fig. 7 and 8. The profile does not change smoothly with time. Instead, there are local changes resulting from variations in the mounting, in the die, or in the substrate mechanical characteristics. Maintaining a uniform remaining silicon thickness requires a sample-processing system that thins to a measured contour and has the capability of altering that contour based on precisely located sample thickness measurements.

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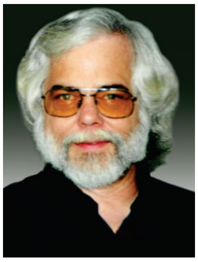
ABOUT THE AUTHORS



Kirk Martin has 40 years of experience in designing and building specialized equipment for all aspects of the semiconductor industry, from crystal growth through final test and failure analysis. In 2005, he became a founder of RKD Engineering, which designs and builds equipment for semiconductor failure analysis and sample preparation. Kirk has patents in the fields of sample preparation, chemical vapor generation, and electrostatic discharge detection and mitigation. His previous positions include Vice President at Nisene Technology Group; Director of Advanced Products at Texas Materials Labs, a manufacturer of specialty semiconductor materials; and Vice President at Automated Technology, Inc., a manufacturer of front-end test and measurement systems.

Nancy Weavers has 30 years of experience in applications in the semiconductor and test equipment industries. She started at National Semiconductor in 1982. In 2006, she became the Chief Executive Officer of Left Coast Instruments, a semiconductor test equipment and electron microscope imaging sales and marketing company. She sits on the Board of Advisors for the San Joaquin Delta Electron Microscopy Program. Previously, she was a Vice President at Nisene Technology Group.