MECHANICAL CHARACTERIZATION IN FAILURE STRENGTH OF SILICON DICE

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ABSTRACT

The trend in die size decrease of the microelectronics circuits has been driven by modern IC manufacturing technology. Due to its brittle nature, high stresses induced in the die due to packaging, assembly and reliability test could result in detrimental fracture in the die. Due to its large diameter and thin layer, determination of the fracture strength of a silicon wafer would be difficult. Thus it is more applicable for silicon strength to be characterized at die level. This paper discusses the approach for the characterization of silicon die failure strength employing a simple three-point bending test, thereby providing a better understanding of the stress accumulated in the die before failure. The effects of die thickness, die size and backgrinding patterns on the die stress have been investigated. The results showed that the die strength is largely dependent on its geometry and damages due to wafer processes (surface/edge defects and backgrinding pattern). A set of thickness dependent threshold stress values for die failure has been obtained for wafers that have undergone mechanical grinding. The determined failure stress values would be useful for solving future die failure problems encountered in new packaging and process development work.

KEY WORDS: Fracture of silicon, wafer processing, surface defect, edge defect, three-point bending test, die failure strength, backgrinding pattern.

NOMENCLATURE

M	Maximum bending moment, Nmm
c	Distance from center of specimen to outer fibers, mm
I	Moment of inertia of cross section, mm^4
F	Breaking load, N
L	Support length, mm
w	Width of specimen, mm
t	Thickness of specimen, mm

Greek symbols

d	Die failure stress, MPa

INTRODUCTION

Over recent years, the rapid advancement in modern Integrated Circuit (IC) technology has led to the continuous shrinkage in the die size and thickness of a microelectronic circuit. The decrease in die size has enabled more functional dice to be obtained in a unit area of the wafer. The reduction in die thickness has also helped in lowering the overall package height profile. Thus the production of smaller and more compact IC packages has been successfully facilitated by all these trends. Inevitably, the issue of high stresses induced in the die due to assembly processes and reliability tests begins to surface. Die related failure has been observed in many flip chip assemblies and multichip packages [1-3]. By nature being a brittle material, moderate stress levels could result in detrimental failure such as cracking and fracture in the die. In addition, wafer processing steps such as thinning and sawing could further induce defects in the silicon die. With different steps of thinning the wafer, surface defects can be introduced. And through wafer sawing, edge defects such as microcracks will be further induced in the die. When subjected to stress loading, there exist a high potential that the microcracks would propagate and result in fracture of the die. As such, die crack or fracture can commonly be resulted during assembly processes or reliability tests. For instance, crack can take place in the silicon die during molding process with extremely high molding pressure or clamping force. Wire bonding onto thin stack die structure could also result in die fracture. The finite element modeling technique can be used to simulate these processes and determine the stress accumulation in the die. The process parameters will be deem inappropriate and need to be re-optimized if the die stress exceeds a certain threshold limit. However, strength (or stress) to failure of the silicon die has not been readily documented in literature. In addition, it is difficult to determine the fracture strength of a silicon wafer because of its large diameter and thin layer that could break easily. It is thus useful if silicon strength or its breaking stress can be characterized at die level.

The two common fields of study for the characterization of a material's failure strength are namely the strength of materials approach and the fracture mechanics approach. In both approaches, the failure strength is dependent on the relevant material properties. By applying the maximum stress theory in the strength of materials study, the material will fail when the maximum principal stress exceeds its ultimate tensile strength [4]. In fracture mechanics study, failure strength of a material not only depends on its material property (yield strength in the case of strength of materials approach), it is also dependent on its flaw size. Failure strength of a homogeneous material can be characterized by the Stress Intensity Factor (SIF) at the crack tip [5]. A crack tip with a definite length is assumed to exist in the material. Upon loading, the stress concentration (or the SIF) at the crack tip begins to build up. When the SIF exceeds the fracture toughness of the material, fracture will occur in the material. It was reported by Mercado et al [3] that silicon has a fracture toughness of 25.9 MPa $mm^{1/2}$. By the finite element modeling of a multichip package, they found that by lowering the SIF of the silicon die (below 25.9 MPa $mm^{1/2}$) with the use of appropriate material sets, die cracking can be eliminated. In many times the strength of materials approach is a simpler and direct way for failure strength analysis of materials, as it is difficult to determine the initial flaw size in a material. However, ultimate strength of the silicon has not been readily established. Thus in this paper the strength of materials approach is adopted, with the intention of extracting the maximum principal stress experienced in the die for the characterization of failure criteria.

The current paper investigates an approach for the characterization of silicon die failure strength, employing a simple three-point bending test technique This is a common method for brittle material testing whereby the breaking load (*F*) to silicon fracture can be determined. And the die strength, *d* (or die stress before failure) can eventually be computed. This helps to provide a better understanding of the amount of stress accumulated in the die before failure, and gives a quick and efficient means of predicting die failure in an IC package through finite element analysis. The effect of variations in the die thickness, die size and backgrinding patterns on the die stress will be investigated. Dummy wafers are used in the current bending test, with limited actual wafers being tested.

CHARACTERIZATION OF BRITTLE FAILURE STRENGTH

Brittle Failure of Silicon

A fracture in the material begins when the stress applied is concentrated at the tip of a microcrack. When the stress exceeds a critical value, atomic bonds begin to break where elastic energy is released. And a new surface is created as the crack propagates through the material. A fracture may be ductile or brittle. In the ductile case, large deformations occur due to boundary slip along the planes of maximum shear stress. In the brittle case, atomic bonds break and the lattice appears to `unzip' behind an atomically sharp crack tip. Brittle fracture is a rapid propagation that takes place without any appreciable deformation. The direction of crack motion is nearly perpendicular to the direction of the applied tensile stress and yields a relatively flat fracture surface. For most brittle crystalline materials, crack propagation corresponds to the successive and repeated breaking of atomic bonds along specific crystallographic planes; such a process is termed cleavage. Macroscopically, the fracture surface may have a grainy or facet texture (refer to Fig. 1).

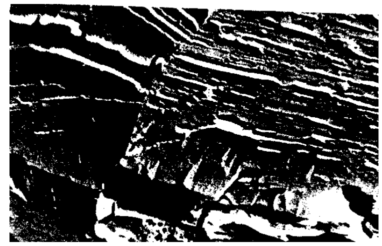


Fig 1. Cleavage Fracture and River Patterns Reflecting Crack Propagation Along Cleavage Plane [6].

Other brittle fracture surfaces contain curved lines called "chevron" markings that seem to converge near the mid thickness of the fracture surface. Chervon markings along the branch will point in different directions relative to the component geometry. It is important to recognize that the different sets of chervon markings all point in the same relative direction - back towards the origin (seen in Fig. 2).

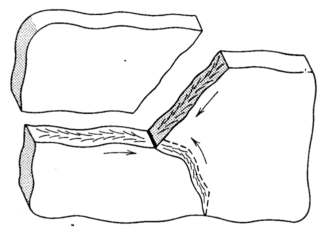


Fig 2. Multiple Chervon Patterns Emanating From Crack Origin [6].

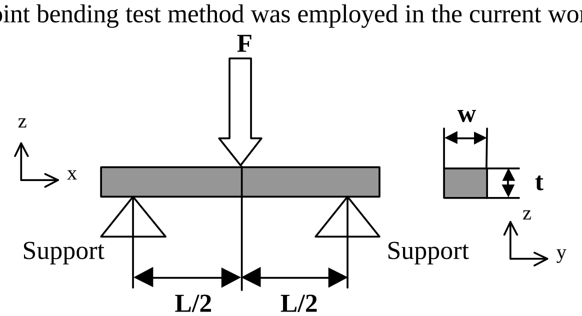
Silicon Wafer Processing - Thinning and Dicing

In the manufacturing of semiconductor wafers and integrated circuits, backgrinding is one of the most important processes. In-coming wafers from wafer fabrication plants usually are in the range of 700 to 800um. It is necessary to thin these wafers to the required thickness to cater for low package height profile. The backgrinding operation is generally done in two phases – coarse grinding and polishing. In most cases, mechanical grinding technique is employed for the thinning process. Abrasive wheels with grit sizes of 300 to 600 are used to grind the wafers to required thickness. Surface roughness or flaws known as *surface defects* are usually resulted after this grinding stage. Following that, finer grit sizes of 1200 to 2000 are used for the polishing of the wafer back surface. This polishing will help to reduce the high residual stresses and surface flaws induced in the wafer backside during coarse grinding. It was found that the use of finer grits would generate silicon dice with a better strength [7-8].

Wafer sawing (or dicing) is carried out for the singulation of dice after the thinning process. Diamond saws are commonly used for the cutting through of wafers. Wafer sawing is another process where mechanical defect could be introduced to the silicon die. During blade cutting, defects like microcracks could be induced along the die edge, thereby resulting in *edge defects* in the die. These flaws would again pose potential regions for crack propagation. Optimal process parameters such as blade exposure time, blade radius and thickness, and cutting rate can help to reduce edge defects thus decreasing the chances of die cracking. It can be seen that the backgrinding and dicing processes inevitably introduce damages to the silicon wafers. These damages will affect the qualities and strength of the die. Therefore to minimize the damages caused to the silicon wafer, the internal qualities of a semiconductor die should be studied in detail and the defects in the process should be identified and reduced to a minimum.

Three-Point Bending Test Method

The failure strength of a material is the maximum stress at the moment of breakage. For silicon material, the stress-strain behavior is not usually ascertained by a tensile test. This is because it is difficult to prepare the test specimens of the required geometry and grip them without fracturing it. Therefore, a more suitable transverse bending test is most frequently employed, in which the specimen is bent until fracture using a three-point loading technique. As illustrated in Fig. 3, the die strength, ***d*** (or die stress before failure) can be computed from the breaking load *F* applied to the silicon die for a given specimen thickness (t) and width (w), and length of the supporting span (L). By symmetry of the loading, the maximum principal stress in the die will lie along the x-axis of the system which equals to the die stress computed by equation (1). During bending the specimen is subjected to both compressive and tensile stresses. The magnitude of its flexural strength is greater than the tensile fracture strength. This is because during tensile test the specimen is only subjected to tensile stress, while in bending both the compressive and tensile stress will balance out each other and the specimen is able to withstand higher stress loading. McLellan et al [7], Erfe [9] and Lee et al [10] have shown the suitability of three-point bending test for silicon die strength study. Other test methods including four-point bending, ball breaker and ring-on-ring test have also been used for investigation purposes [8,11]. However due to the unavailability of these tools, three-point bending test method was employed in the current work.



$$d = stress = \frac{Mc}{I} = \frac{3FL}{2wt^2} \qquad (1)$$

where M = maximum bending moment = FL/4
c = distance from center of specimen to outer fibers = t/2
I = moment of inertia of cross section = $wt^3/12$
F = breaking load (N)
L = Support length (mm)
w = width of specimen (mm)
t = thickness of specimen (mm)

Fig 3. Three-point Loading Schemes for Measuring the Failure Strength of the Silicon Die.

Through a three-point bending test, the strength of the silicon die can be largely dependent on the wafer/die processing history. In the first instance, wafer fabrication processes like photolithography and etching will induce sites of high stress concentration. The different passivation layers used by wafer plants may also play a part in affecting the strength of the die. Secondly, the different techniques and process parameters in mechanical grinding and polishing will determine the seriousness of flaws or scratches remained on the wafer backside. In addition, the difference in orientation of scratch lines on the backside of the individual chips due to abrasive grinding will give rise to different die strength with respect to the bending axis. As shown in Fig. 4, a die taken from region 2 would withstand a lower breaking load as compared to a die resided in region 1. The reason being any surface microcrack running in parallel with the bending axis could propagate easily. While for the backgrinding pattern in region 1, the scratch lines are perpendicular to the bending axis, thus resulting in higher flexural strength.

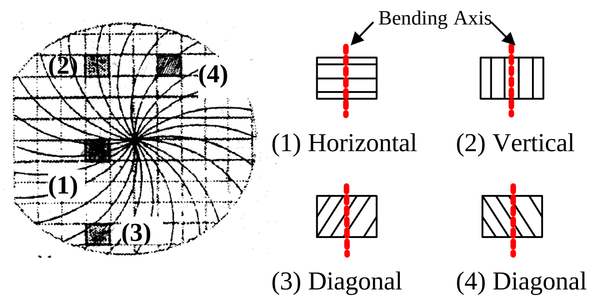


Fig 4. Backgrinding Pattern Corresponding to Different Positions of the Wafer and Bending Axis.

EXPERIMENTAL BENDING TEST SETUP

Multiple sizes and thickness of the silicon dice were collected for the three-point bending test. For each configuration, a sample size of thirty-two were being tested utilizing the Instron Micro-Force Tester. It was further divided into eight specimens for each backgrinding pattern described in Fig. 4. To remain consistency in comparing die of different lengths, a constant support span of 4mm was used throughout the test. The rate of the crosshead motion (loading pin) was set at 0.5mm/min. During loading, a load-vs-deflection graph was plotted and the maximum load at die fracture was recorded for analysis. All test wafers and dice undergone similar mechanical backgrinding and sawing steps to avoid discrepency in test results due to manufacturing processes.

RESULTS AND DISCUSSION

In material testing the three-point bend method gives rise to a maximum bending moment at the specimen centre, thus not capturing the surface or edge defects that is away from the die centre. A four-point bend test results in a uniform moment across the specimen within the loading pin, thereby the die will fracture at a point where surface or edge defect is the largest (and not necessary located at die centre). Therefore it is a better method than three-point bending for capturing a randomly distributed nature of surface and edge defects. As such the die strength obtained from the three-point bend test would always be higher than the four-point bend test, and a more lenient failure criteria for die cracking.

Effects of Silicon Thickness on Die Strength

Thickness ranging from 0.15mm to 0.394mm of the silicon dice were tested under bending load. The load to die fracture for thirty-two specimens were recorded, with the maximum, minimum and average values being plotted in Fig. 5. The result generally shows an increasing trend of the die breaking load with die thickness. This is expected as a larger load is needed to cause breakage in a die with a greater volume. A slight drop in the breaking load from die thickness of 0.3mm to 0.32mm was observed. And the standard deviation of test values for 0.394mm die thickness appears to be higher than the rest. The reason could be attributed to the random distribution of the surface and edge defects induced in the silicon dice. The affected specimens could have subjected to greater damage during the backgrinding and dicing processes. Nonetheless, a clear increasing trend in the breaking load is noted.

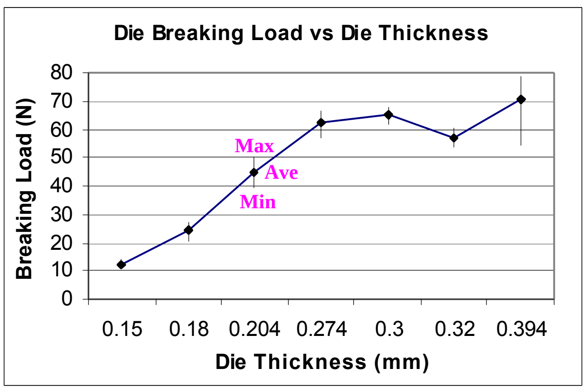


Fig 5. Die Breaking Load for Different Die Thickness.

The die stress (max. principal stress) at failure was next computed using equation (1) with the breaking load obtained. It was anticipated that while different load is required to cause fracture in the die with different thickness, the die stress at failure should be constant throughout. In other words, the die strength should be the same for all thickness. However in contrary, varying die stresses were captured for different thickness. In Fig. 6, the die stress at failure obtained ranges from 300 to 1000 MPa for a die thickness of 0.15 to 0.394mm. With a die thickness of 0.3mm, McLellan et al [7] reported a failure stress of approximately 300 MPa versus the 544 MPa obtained in the present work. The difference noted could be due to the testing of different wafer types. Actual wafers were used in McLellan et al bending whereas dummy wafers were used in the current test. The comparison of die strength between actual and dummy wafers will be discussed in the later section. The die failure stress in Fig. 6 increases when the die thickness decreases from 0.394mm to 0.204mm. A turning point exists when the die thickness falls below 0.2mm, and the die stress decreases with decreasing thickness. This trend suggested that the die strength actually increases when it is thinner, up to a thickness of 0.2mm. In a thick die, it is more rigid when subjected to a bending load. Thus it is not able to withstand higher stress and fail earlier. A thinner die will be more flexible under flexure load, and it is capable of absorbing higher stress before failing. However when it reaches a critical thickness where the die becomes too thin (in this case < 0.2mm), there is not sufficient material to sustain its flexibility. As a result, the die is no longer able to withstand higher load and starts to fall apart. With this observation, extra attention should be given to the solution for very thin package profile using ultra thin die. More cautious measures should be put in place for process assembly and handling of ultra thin wafers/dice.

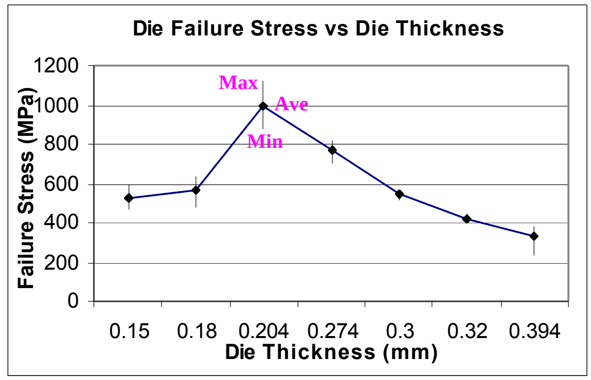
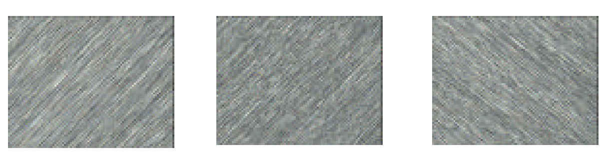


Fig 6. Die Failure Stress for Different Die Thickness.

In another case, the die strength could be affected by the seriousness of the surface defects induced after backgrinding. A rougher die surface (with larger and more flaws) would be more prone to fracture failure, and thus constitutes to a lower die strength. The trend observed in Fig. 6 could therefore be due to a variation in seriousness of the surface roughness, rather than geometric effects. Metrology techniques like the AFM (Atomic Force Microscopy) can be used to measure the surface roughness of a backgrinded wafer, hence helping to monitor and keep surface defects to a minimum. Unfortunately surface analysis could not be performed for all completed test parts. A new set of test wafers with thickness ranging from 0.1mm to 0.3mm will be subjected to bending test. Surface analysis was conducted using optical microscope (due to the unavailability of AFM equipment) with the surface texture shown in Fig. 7. It was found that similar rough texture was observed over all different die thickness. Die failure strength will be reported in a later stage, and the trend of die strength versus thickness to be further analyzed.



a) 0.1mm   b) 0.16mm   c) 0.25mm

Fig 7. Microscopic Images of Die Backside Surfaces for New Test Wafers.

Effects of Silicon Size on Die Strength

The effect of die size on its failure strength is evaluated next. Since the support span was fixed at 4mm for all tests, the length of the specimens would not have any impact on the test results. In this analysis, dice with a constant thickness but different widths were looked into. Results from specimens with a die thickness of 0.3mm and widths of 6, 6.52 and 8mm were extracted. Fig. 8 illustrates the response of the die breaking load and strength. Both the load and stress values increase with the die thickness. As the width of the specimen increases, any crack in it needs to propagate through a longer grain boundary before failing the entire die. Therefore a larger amount of force will be required to fracture a larger specimen, and in return contributed to stronger die strength.

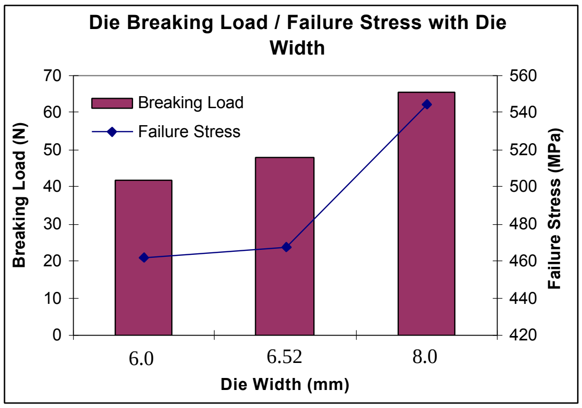


Fig 8. Die Breaking Load and Failure Stress for Different Die Sizes.

Comparison Between Wafer Types

With the known fact of the high cost of actual functional wafers, dummy wafers (also known as mirror wafers) are commonly used for process parameters optimization and DOE (design of experiments) study. It is therefore important to know the difference in strength between the wafer types, and any optimized parameters obtained based on dummy wafers to be adjusted or modified (if necessary) to suit the actual wafers. It is understood that there exist some differences in the processes steps between dummy and actual wafers. Although both wafer types will undergo similar backgrinding and dicing processes in a same factory, actual wafers have gone through extra manufacturing process (like photolithography and patterning) prior to backgrinding. Sets of dummy and actual wafers were tested for comparison, with two different die thickness of 0.155 and 0.3mm. It was found that the strength of the dummy die is higher than the actual die (refer to Fig. 9). The wafer manufacturing processing experienced by the actual wafers has indeed induced further damage to the wafers. The trend is well observed in the earlier section where actual wafers tested by McLellan et al has a lower breaking stress than the dummy wafers tested in the current work.

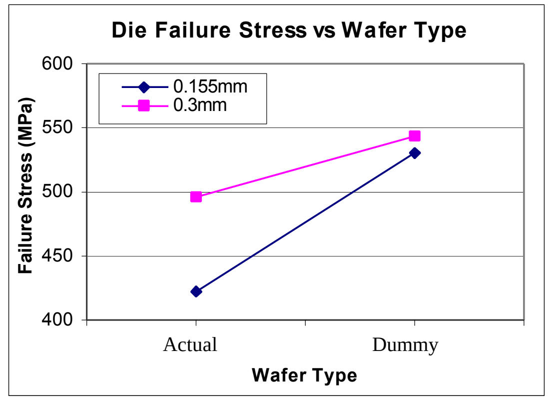


Fig 9. Comparison in Die Strength of Different Wafer Types.

Effects of Backgrinding Pattern on Die Strength

In order to analyze the effect of backgrinding pattern on die strength, a set of test data for die thickness of 0.16mm was separated according to the backgrinding pattern and plotted in Fig. 10. It was found that a grinding pattern running perpendicularly to the bending axis has yielded the maximum breaking load and failure strength. And a lowest die strength was obtained by dice with grinding pattern in parallel with the bending axis, while the diagonal grinding pattern has generated strength in between. The reason has been explained earlier that surface microcrack running in parallel with the bending axis could propagate much more easily. Similar trend has been observed by research work conducted earlier [7,9].

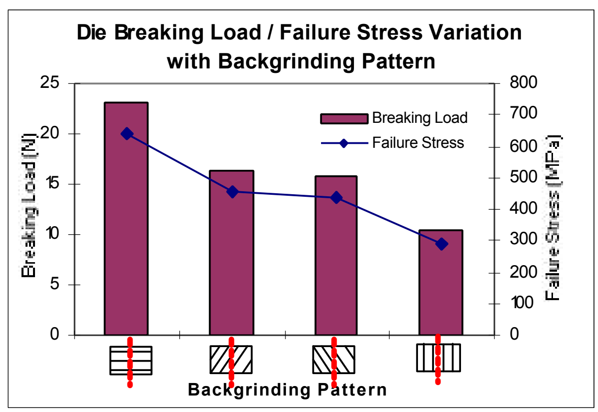


Fig 10. Die Breaking Load and Failure Stress for Different Backgrinding Patterns.

Macroscopic Analysis

In aid for post-test failure analysis, fractured parts of the silicon dice were gathered after the bending test. Fig. 11 shows the surface of a fracture silicon die in magnification of 5x by an optical microscope. It was observed that the silicon die was under brittle fracture with the surface clearly showing cleavage facets (“river patterns”) texture.

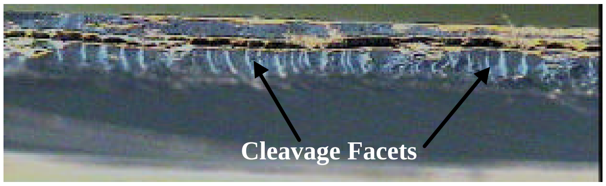
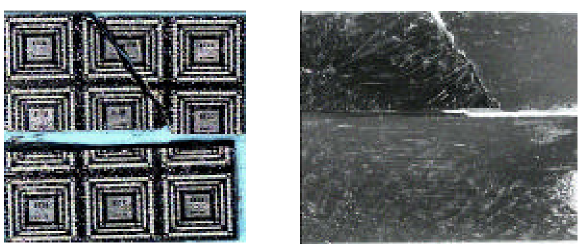


Fig 11. Surface of a Fracture Silicon Die Showing Cleavage Facets.

Fig. 12 shows the brittle fracture of an actual die and a dummy die respectively. It contains curved lines called "chevron" markings. The "chervon" markings all point in the same relative direction - back toward the origin revealing the dominance of die weakness due to surface defect. Yeung et al [12] reported that a backgrinded die with a more severe surface damage that usually resulted from mechanical grinding tends to break down into few pieces and gives a lower strength. Whereas dice with smoother surfaces obtained from wet chemical etching will fracture in a shattering pattern due to the great elastic energy released when crack propagation starts. The observation thus gives an evidence that large surface roughness is present in most of the tested wafers due to mechanical grinding. Wet etching chemical process could be introduced to the backgrinding process to reduce the surface roughness of the silicon wafers thus helping to increase the die strength.



i) Actual Die ii) Dummy Die

Fig 12. Fracture Actual and Dummy Silicon Dice Showing "Chervon" Marking.

Finite Element Modeling

The die stress at failure is computed using equation 1 being derived from the beam bending theory. A three-dimensional (3D) finite element model of the silicon die was created to simulate the bending test to check on the validity of the die stress values obtained. *ANSYS 7.0* was used to perform the analysis with the use of element type 45 (linear element) in representing the problem geometry. The average breaking load taken from the experimental results was prescribed in the model to simulate the loading condition.

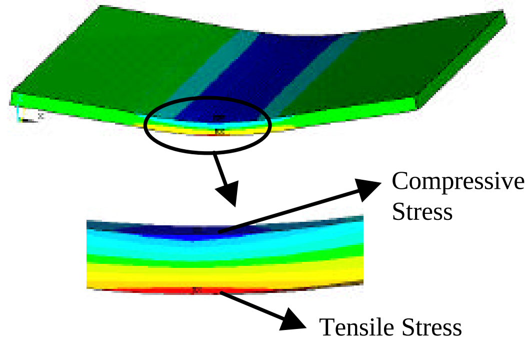


Fig 13. Contour Plots of Silicon Die after Loading.

The die stress contour at the end of the loading is shown in Fig. 13. The silicon die bends downwards with a maximum tensile stress at the bottom of the die, and a compressive stress at the upper surface. The tensile stress values (max. principal stress) taken from simulation results were compared with experimental measurements reported earlier. As seen in Fig. 14, the simulation results correlated very well with experimental data, with variations of less than 6%. It does show that the use of the beam bending equation is acceptable for the computation of die bending stress, and that the finite element modeling technique can capture the stress accumulated in the die accurately over different thickness. Thus a robust simulation model using element type 45 can be established for future die stress computation and prediction.

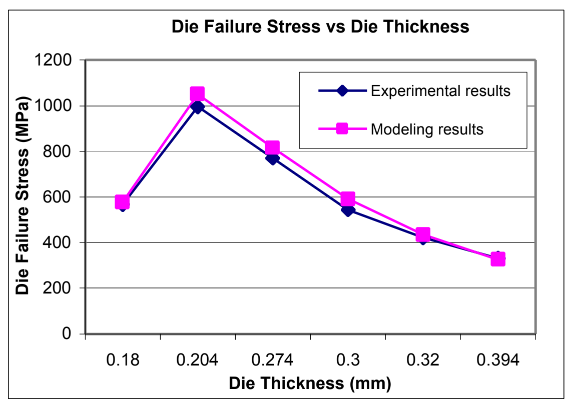
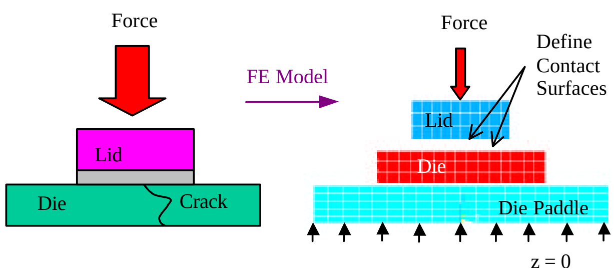
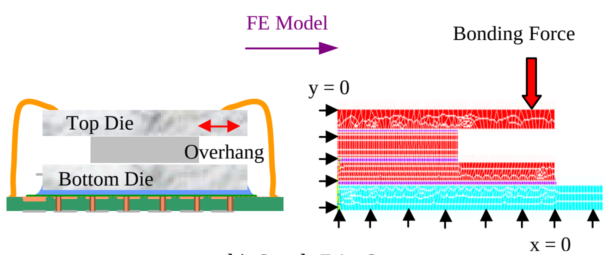


Fig 14. Correlation of Simulation and Experimental Results on Die Bending Test.

To assist in the check on the suitability of finite element modeling in solving IC package related problems, two case studies were conducted. In the first case with a Quad Flat No-Lead (QFN) package, a metal lid is to be attached onto the silicon die in aid of better thermal dissipation (see Fig. 15a). With the high molding pressure and clamping force, a reduction in lid surface area will exert a larger pressure on the die. With a die thickness of 0.25mm, die cracks were found in packages with a small lid. The die failure stress as indicated in Fig. 14 equals approximately 900MPa. Finite element modeling was performed based on actual loading conditions with the small and a recommended (larger) lid sizes. The die stress decreased from a high of 1140MPa to a low of 440MPa when the lid size is enlarged. Thus the larger lid was implemented in the QFN design and the die cracking issue was resolved. In the second example, wire bonding onto thin stack die structure (Fig. 15b) could result in possible fracture of the top die. Wirebonding at the overhang of the top die replicates a cantilever loading where high stress will be experienced at the pivot point. FE modeling was performed for the worst case scenario, i.e. thin die with a long overhang. It was found that the maximum stress generated was much lower than the actual die breaking stress. Thus no fracture in the top die was encountered. The above two cases showed the use of finite element simulations coupling with experimental die failure strength in containing possible die fracture during assembly processes.



a) Metal Lid on Die



b) Stack Die Structure

Fig 15. Case Studies for Finite Element Simulations.

Based on the strength of materials approach, the silicon die can be modeled as a bulk material in finite element analysis. The maximum principal stress can be easily extracted hence giving a quick and efficient means of assessing die failure in an IC package. In contrary for fracture mechanics, the flaw size has to be pre-determined for failure analysis, and mesh-size dependent crack tip model has to be created. It is almost impossible to measure the flaw length of every die tested, and those that are mounted in an IC package. Hence it is recommended for the strength of materials approach to be employed for the first pass of die failure indication, with detailed crack analysis performed using the fracture mechanics technique if necessary.

CONCLUSIONS

The characterization of the failure strength of the silicon dice using a simple three-point bending test has been investigated. The maximum principal stress in the die before failure during bending test is captured as the failure strength. The study shows that the die strength is largely dependent on its geometry (thickness and size) and damages due to wafer processes (surface/edge defects and backgrinding pattern). The use of various backgrinding methods such as mechanical grinding and wet etching will result in different levels of surface roughness. Macroscopic investigation revealed the influence of surface damage on die strength and should not be neglected. A set of thickness dependent threshold stress values for die failure has been obtained for wafers that have undergone mechanical grinding. However, the collected data up to the present stage is not able to account for die strength of all thickness (especially the ultra thin wafer). In addition, a less stringent failure criteria is generated utilizing the three-point bend test. Thus the compilation of a comprehensive failure data will be continued. Lastly, case studies were performed to demonstrate the coupling of finite element simulations with experimental failure strength in solving die failure problems encountered in packaging and process development work.

FUTURE WORK

Further data collection will be conducted for the compilation of a comprehensive database for the failure strength of different die thickness. Ultra thin (<100um) wafers fracture strength evaluation will also be performed. Impact of surface and edge defects on die strength will be looked into.

ACKNOWLEDGEMENT

The authors would like to express their sincere appreciation to Dr Anthony Sun and Rahul Kapoor for the support in the research project, and Thomas Chiah and Kellin Ng for the preparation of the wafers for bending test.

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