Effect of Die-Attach Adhesives on the Stress Evolution in MEMS Packaging

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Abstract

A device performance of *MicroElectroMechanical System* (MEMS) inertial sensors such as accelerometers and gyroscopes is sensitive to the stresses developed in the silicon die during packaging processes. This is related to the die warpage in the presence of the stresses. Previously, it has been shown that most of the stresses are generated during the die-attach process. Given that, we assess the stress development at the die-attach stage by measuring a curvature of small dummy silicon dies (3.5x3.5 mm^2) bonded to the substrates using three different adhesives (silicone, polyimide, silver glass). For this purpose, a non-contact, optical surface profilometer is employed, which can measure the die warpage in nanometer scales. In addition, structural parameters such as the adhesive thickness and material properties are examined to highlight their effect on the stress development with the aid of finite element analysis (FEA). A stress model proposed from this study will not only provide a diagnostic tool for very small devices, but it will also offer a design tool for low-stress MEMS packaging systems.

Key words: MEMS packaging, Stress, Profilometer, Warpage, Die-attach, Adhesives, Finite element analysis

I. Introduction

MEMS technology integrates mechanical elements, sensors, actuators and electronics onto a common substrate by applying so called micro fabrication that is similar to the CMOS fabrications in microelectronic industry [1-3]. Over the years these devices have become smaller, cheaper, more functional, and reliable to use. Packaging of the MEMS devices and systems, however, still faces major challenges as nearly all the MEMS packages are application specific with most of them demanding a direct contact with the environment.

The packages should also be free from residual stresses that are developed during the course of the packaging processes, followed by thermal cycling environment [4]. Therefore, it is essential to understand the origin and evolution of these stresses in order to improve the reliability of the MEMS packaging systems. Another major concern regarding the die attaching materials for MEMS packaging is the long-term drift resulting from slow creep in the adhesive due to these stresses along with the chemical and mechanical stability of the interfaces formed with the die and the substrate materials at high temperatures.

Our previous study indicates that most of the die stress is developed at the curing of the die-attach adhesives. This stress makes the silicon die warped, and its development seems to influence the performance of the MEMS sensors. Therefore, it was suggested that the stress testing protocol be used as a diagnostic tool to determine the device performance of MEMS sensors [5].

Given that, the main focus of this work is to examine the evolution of the die stress assembled to the ceramic packages by measuring the warpage (curvature; out-of-plane displacement) set up during the curing of the adhesives and related processes. For this purpose, we employ an optical profilometer that has a capability to scan a wide range of height information (0.1 nm to 500 μm) [6]. Microstructural evolution of the adhesive layers and interfaces during thermal treatments are also post-examined to better understand the stress development.

We have exploited both experimental approaches and numerical simulation to study the packaging stresses. One advantage of this simulation tool is that it can aid to explore a much larger range of parameter space (temperature, materials, geometry, etc.) than is practical experimentally. The collective information will be used to better understand certain experimental observations, and also to steer into the development of the improved packaging system.

II. Experimental Procedure

In an attempt to identify the stresses in silicon dies, a non-contact, optical profilometer was utilized to measure warpage of the die by tracing its surface profile. The stresses in the die can then be deduced from the profiles across the surface, according to theory of elasticity:

$$\sigma_x = \frac{Et(1/R_x + \nu/R_y)}{(1-\nu^2)} \qquad (1)$$
$$\sigma_y = \frac{Et(1/R_y + \nu/R_x)}{(1-\nu^2)}$$

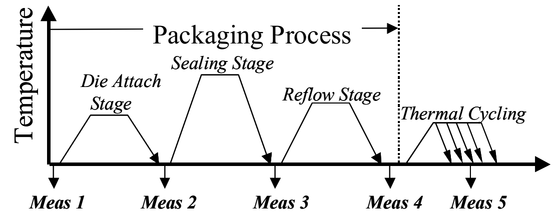
where E is Young's modulus, ν is Poisson ratio, t is a half of the thickness of the die, and R_x and R_y is the radius of curvature in the x- and y-direction, respectively [7,8]

Surfaces of the dummy silicon dies (3.5x3.5 mm^2), assembled into different types of ceramic packages with the help of three different die attach adhesives (silver glass, polyimide, silicone) were profiled for the stress testing. For a reference, bare silicon dies, which were cut from the silicon wafers, were also examined for an initial warpage measurement. These packages were further tested with a series of heat treatments to mimic the actual packaging processes as well as device operating conditions to understand the evolution of these stresses. Figure 1 shows the heat treatment conditions used for the stress testing packages and the stress measurement schedules. All the measurements were performed at room temperature, and each sample was measured twice (non -consecutively).

In order to investigate microstructural features of the die-attach adhesive and its interfacial integrity, microstructural characterization was performed via both optical microscope (OM) and scanning electron microscope (SEM). In particular, the samples were potted in an epoxy mold, cross-sectioned by a diamond saw machine, and metallographically polished with a 1-micron diamond slurry finish to reveal each different region. In this way, we could also measure thickness of the die-attach adhesive layer between the silicon and the substrate.

III. Simulation Methodology

In order to understand better some experimental results as well as to have a predictive capability, we have also adopted numerical simulation in this study. A simple 2-D model was developed based on the center cross-section of the package using the ANSYS software package [9]. The material properties for silicon, ceramic and the adhesive layer were assumed



Packaging Processes	Experimental Conditions
Die attach	**Silver Glass** cured at 355°C. **Polyimide** cured at 100°C for 30 min and 200° C for 30 min. **Silicone** cured at 150°C for 60 min.
Solder Sealing Process	Peak temp of 340°C
Solder Reflow Process	Peak temp of 240°C

Figure 1. Standard packaging processes followed by thermal cycles and corresponding heat treatments used in this study for the stress measurement.

to be linear-elastic. Since the package is symmetric at the center, only half of the package was modeled (Fig. 2). In order to estimate the deflection occurred during packaging processes, the silicon die was exposed to a heating/cooling cycle. This simulation was performed with heating at 350˚C followed by cooling down at 27˚C to emulate the package sealing process. This condition was chosen to compare the simulation result with experimental test results. Since the model only assumes an elastic deformation, only half-cycle was considered for the analysis.

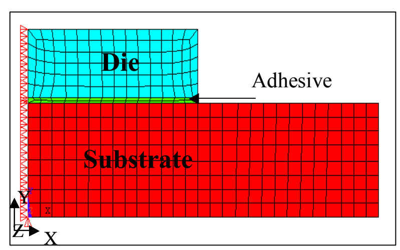


Figure 2. Geometry of the 2-D model used in the simulation.

IV. Results and Discussion

Figure 3 shows 3-dimensional surface profiles of the silicon die attached to the ceramic substrate. As seen here, a dome-shaped surface profile was found, indicating the die warpage. The profile was acquired after the test package was die attached and heat treated for a solder sealing process. In order to estimate the warpage (curvature), a line profile across both x-direction and y-direction were drawn. Most of surface profiles obtained from this study show uniform stress distribution (circular-dome shape)

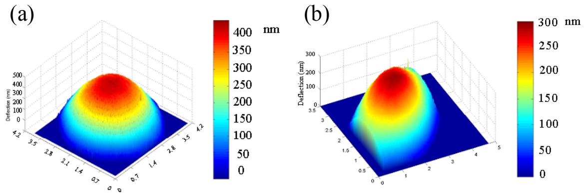


Figure 3. 3-D surface profile of the silicon die showing (a) uniform deflection (b) non-uniform deflection for the sidebraze package assembled with the silver glass and the polyimide adhesive, respectively.

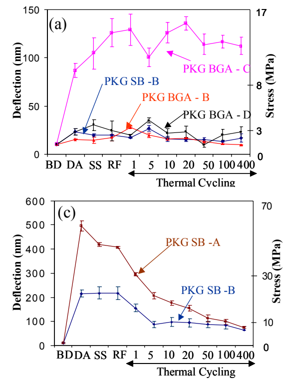
(Fig. 3(a)) though non-uniform elongated warpage shapes were also observed as shown in Fig. 3(b).

Stress Evolution during Manufacturing Processes:

Figure 4 shows evolution of the stresses during a series of heat treatments that mimic the packaging processes and thermal cycling. It is seen that the packages with the silicone adhesive show the lowest stress development. This stress level was almost the same as the one observed for the bare silicon. The PKG BGA-C, however, shows higher stresses than the other package designs, and these stresses gradually increase during the packaging heat treatments until the reflow stage. Some modification in the packaging design (i.e., PKG BGA-D) was beneficial in reducing the stresses as compared with the PKG BGA-C as shown in Fig. 4 (a).

For the polyimide adhesive, it is shown that maximum stresses are built up during the die-attach process (sometimes, after the solder sealing process) and are maintained for the rest of the packaging processes (i.e., corresponding heat treatments) as well as thermal cycling up to 400 cycles (from -55ºC to 125ºC) as shown in Fig. 4 (b). Also, it is noted that there was a variation in the stress development for the same packages, which could be due to a variation in manufacturing processes causing a structural change in the package.

The stress in the silicon die attached with the silver glass was quite high. Again, some modification in the package design (PKG SB-B) dramatically reduces this stress level as shown in Fig. 4 (c). Interestingly, the stress seems to continuously decrease during heat treatments. It suggests that there exists a stress relaxation mechanism for the silver glass adhesive, which was not present for the polymer-based adhesives such as polyimide and silicone. The stress levels between silver glass and the polyimide after several thermal cycles therefore exhibit a similar value due to the stress relaxation.



Package Type	Package Variations
Sidebraze (SB)	Type A (PKG SB-A) Type B (PKG SB-B)
Ball-grid array (BGA)	Type A (PKG BGA-A) Type B (PKG BGA-B) Type C (PKG BGA-C) Type D (PKG BGA-D)

BD – Bare Die, DA – Die Attach, SS – Sealing Stage, RF – Reflow Stage

Figure 4. Stresses set up in silicon die during a series of heat treatments for different packages using (a) silicone (b) polyimide (c) silver glass adhesives. The error bar represents the stresses in the x- and y-direction.

Possible explanations for this behavior include interfacial delamination during testing, crack initiation in the glass phase, and creep of the adhesives. Since we did not observe a significant proportion of cracks or delamination after the test (see Fig. 9), it is unlikely that the cracks can explain this significant reduction in the stress development. Therefore, creep deformation of the silver glass might be responsible for the stress relaxation in the die at elevated temperatures. In fact, this stress relaxation behavior was also reported in the literature [10-12]. Because of this behavior, the silver glass can be preannealed in order to reduce the initial stress level for the package assembled with it.

Effect of Thickness of Die-Attach Adhesives:

The thickness of the die attach adhesive plays a major role in reducing the stress development since the adhesives can accommodate the stresses developed due to the CTE mismatch between the silicon die and the ceramic substrate. Since the adhesives shrink during curing, it must also be minimized for better performance of the die-attach adhesives. In addition, actual packaging processes result in a significant variation in thickness of the adhesives. Therefore, it is of great importance to know about the thickness effects.

Figure 5 shows the aforementioned thickness effects observed in the silicon die. Three die-attach adhesives are compared after reflow stage. It is seen that the stress decreases as the thickness increases for the ceramic plate packages assembled with a silver glass adhesive. However, the stress was rather constant with thickness for the polyimide and silicone adhesives.

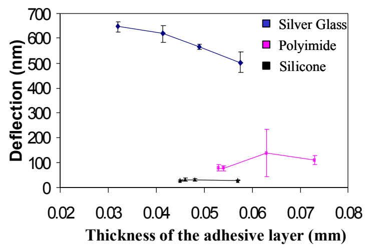


Figure 5. Effect of the die-attach adhesive thickness on the deflection developed in silicon die

In fact, the decreasing behavior is expected since the thicker adhesive can act as a buffer layer to accommodate the stresses resulting from the CTE mismatch between the silicon and the ceramic substrate [13]. It seems that the polymer-based adhesives may have other effects such as shrinkage during curing in addition to the CTE mismatch effect that causes the stress development in the die.

Our simulation result, however, shows that the deflection in the silicon die decreases with an increase in thickness of the adhesive layer for all of the three adhesive cases. The magnitude of the deflection obtained in the simulation was rather high, compared to the experiments. This discrepancy may be attributed to the basic assumption of linear material properties, which is less realistic for the adhesive layer, and can be minimized by introducing non-linearity in the model. In addition, temperature-dependent materials properties and the 3-D model may help to further reduce the difference between the simulation and experimental results.

Also it is shown that the stress distribution in the silicon die becomes uniform (i.e. from tension at the top left corner to compression at the bottom left corner of the die in Fig. 2) with an increase in the thickness of the die-attach adhesive layer (Fig. 6). One possible explanation for this is that, with an increase in the thickness of the adhesive layer, the substrate and the die gets decoupled each other and the thermal stresses in the silicon die are solely influenced by the material properties and the configurations of the adhesive layer. The package with the silver glass needs a thicker adhesive layer to have uniform stress distribution than that with the polyimide.

Figure 7 shows a displacement of the silicon die at the top surface when the package is cooled from 350 to 27˚C. The displacement in silicon die gradually decreases toward the edge of the die. The displacement was smallest for the silicone adhesives (note on the y-scale), which is consistent with experimental results. The silicon die with a silicone adhesive displays a maximum σ_{xx} at the center of the

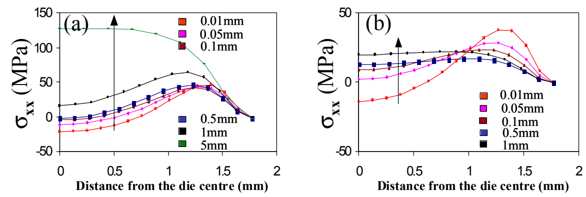


Figure 6. Stress distribution observed along the top surface of the silicon die for different die attach thickness for (a) silver glass (b) polyimide through numerical simulation. The arrow mark indicates a direction of increasing thickness.

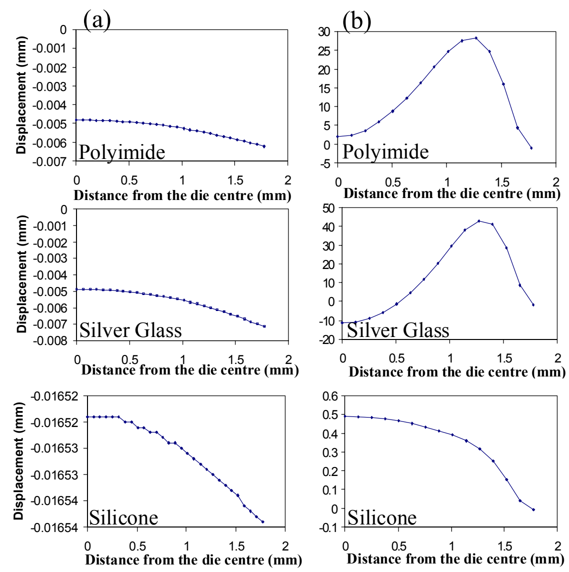


Figure 7. Simulation result of (a) displacement (b) stress in the x-direction, observed along the top surface for the three different adhesive types using 0.05mm adhesive thickness. Note the scale in the displacement.

die along the die surface, while with polyimide and silver glass the maximum stress is observed near the edge of the die. It suggests that it is beneficial to place the stress-sensitive structures and components close to the low stress location (either at the center or in the corner) depending on the adhesives used and their thickness.

Effect of Material Properties:

As shown before, the packages assembled with different adhesives behave differently in terms of the stress development. In order to characterize the effect of material properties such as Young's modulus and CTE, we have compared the deflection by adjusting these values. As shown in Fig. 8, Young's modulus has a significant impact on the stress development while the CTE has little impact on this. For example, by reducing the modulus value for the silver glass, the deflection value decreases substantially. Therefore, it is clear that the adhesives having lower Young's modulus such as silicone will be a good choice for reducing the stresses in MEMS packages. On the other hand, since both silicon and ceramic layers are stiffer and thicker than the silver glass, the CTE effect does not become important until it reaches at very large values.

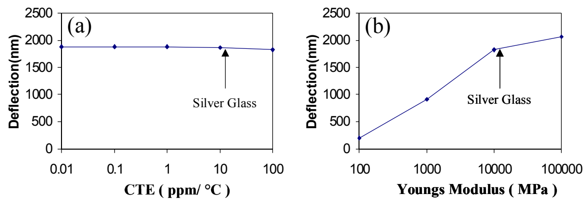


Figure 8. Effect of materials properties of the adhesive layer on warpage set up in the silicon die (simulation result): (a) CTE; (b) Young's modulus. The arrow mark indicates the properties of silver glass adhesive.

Microstructure Characterization of the Silver Glass Adhesive:

Microstructural characterization of the test packages was carried out to correlate it with the stress development of the silver glass adhesive. For this experiment, the packages were heat treated with the same procedure as mentioned earlier, and at each stage, we focused on the same areas with SEM after cooling down to see whether there was any drastic change in the microstructure of the silver glass. Figure 9 shows the same area at different stages of heat treatments (from die-attach to 400 thermal cycles). It seems that microcracks occur and some glass phases evolve at the silicon die and adhesive interface right after the reflow process (Fig. 9 (b)), but no significant change occurs after this process. It is noted that the stress relaxation behavior was observed until the 400 thermal cycles, indicating that microcracks did not evolve significantly during a series of heat treatments. Therefore, the crack generation in the adhesive layer and/or at the silicon/adhesive interface cannot explain the stress relaxation mechanism for the silver glass. This observation supports the creep deformation of the adhesive layer at elevated temperatures as a stress relaxation mechanism.

While performing this study an interesting feature for the silver glass was observed (Fig. 10). These images indicate that an amount of the glass phase observed in the central region is less than that

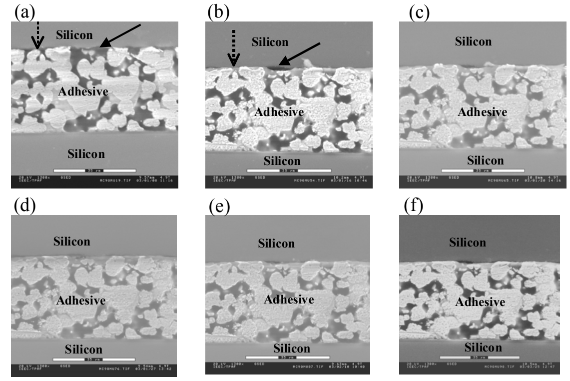


Figure 9. SEM images showing microstructural evolution of the silver glass adhesives after a series of heat treatments: (a) die-attach stage; (b) reflow stage; (c) 10 thermal cycles; (d) 50 thermal cycles; (e) 100 thermal cycles; (f) 400 thermal cycles. The arrow marks (┈➤) show glass phase evolved and microcrack developed (➔).

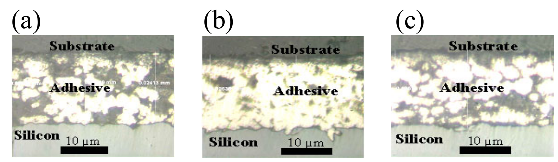


Figure 10. OM images showing the silicon die, the silver glass adhesive, the ceramic substrate at three different locations of the package: (a) left edge; (b) center; (c) right edge. The light phase in the adhesive represents silver and the dark phase represents glass

observed at the corners (i.e., left and right edge), which might indicate that the glass is flowing more towards the outer corners during the die-attach heat treatments. This behavior has also been observed by other researchers [14,15]. This glass segregation behavior during die-attach stage may provide an interesting clue as to how the silver glass behaves under stress at elevated temperatures. Further experiments are underway to correlate it with the stress behavior.

V. Conclusion

The optical profilometer was successfully applied to measure a small amount of warpage (curvature) occurred due to the stress in the silicon die (about 20-700 nm deflection for most of the cases). Among the three different adhesives used, the silicone adhesive outperforms the other two types of adhesives in terms of stresses developed in the silicon die due to its low modulus. It can act as an effective buffer layer when sandwiched between the die and the substrate.

When mimicking the actual packaging process, it is shown that the die-attach stage induces most of the stresses in the die, and extensive thermal cycling does not further increase the stress levels. Therefore, it is important to control the stress development at the die-attach stage. In addition, the silver glass assembled package indicates the stress relaxation behavior, resulting in a similar stress value to the polyimide package after several steps of heat treatments. This stress relaxation behavior can be related to the creep deformation of the silver glass adhesives at elevated temperatures.

Microstructural characterization of the silver glass revealed some interesting features. In particular, segregation of the glass phase always occurs in the outer edge of the adhesive layer after the die is attached to the substrate and cured. Further studies are needed to better understand this behavior of the silver glass.

Our results indicate that warpage (i.e., stress) in the silicon die can be minimized by using relatively thicker adhesive layers though some adhesives do not follow this expectation. Numerical simulation also indicates that stress can be relieved by having the adhesives with lower modulus. These parameters, of course, must be balanced with other factors in overall manufacturing designs and processes. The stress distribution at the top surface of the silicon die can also depend on the thickness and modulus of the adhesives. Importantly, this stress testing protocol can not only be used as a tool to monitor the device performance of the MEMS packages, but it can also be used as a tool to design low-stress MEMS package systems.

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