High Reliability Second Level Interconnects Using Polymer Core BGAs

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Abstract

The growing need for shorter interconnects for better electrical performance has shifted package designs more and more towards ball grid arrays (BGAs). This has brought into focus the requirement for a reliable second level interconnect. Due to the thermal mismatch between the package material (e.g. ceramic) and the PWB board the solder interconnects are prone to failure during temperature excursions. Increasing the interconnect height by using a larger diameter ball may increase the mechanical reliability, but would compromise the electrical performance. So there needs to be an interconnect solution to getting good reliability without compromising the electrical properties.

This paper compares the mechanical reliability and electrical performance of a novel interconnect material with the conventional solder ball. The new solder ball consists of a core of polymer with a thin layer of copper with additional covering of solder which could be either tin/ lead based or lead free. Temperature cycling data was obtained from both conventional and polymer core balls tested on ceramic packages mounted on a FR4 board. Weibull data showing the differences are plotted and failure analysis is done on the failed parts to understand the different failure modes between both the types of BGAs.

An electrical simulation was done to compare the polymer-core ball with a conventional solder ball. DC resistance analysis and a full-wave electromagnetic RF simulation were performed to compare the two types.

Introduction

BGA technology offers many advantages [1] over other technologies like QFPs, and PGAs. BGAs not only result in higher pin counts or smaller packages but also considerably higher manufacturing process yields can be achieved. BGAs are also beneficial with respect to reduced coplanarity issues, reduced placement problems (self aligning) and better electrical and thermal properties. But BGAs are not without their share of problems. The most critical being the second level reliability concerns. This issue is being addressed with great urgency by not only the end-users but also assemblers and material suppliers.

Second Level Reliability

When a device is exposed to cyclic changes in temperatures during its actual use, it induces thermal expansion mismatches between the substrate and the board.

This creates cyclic shearing loads on the solder interconnects (BGA joints), which eventually leads to their fatigue failure.
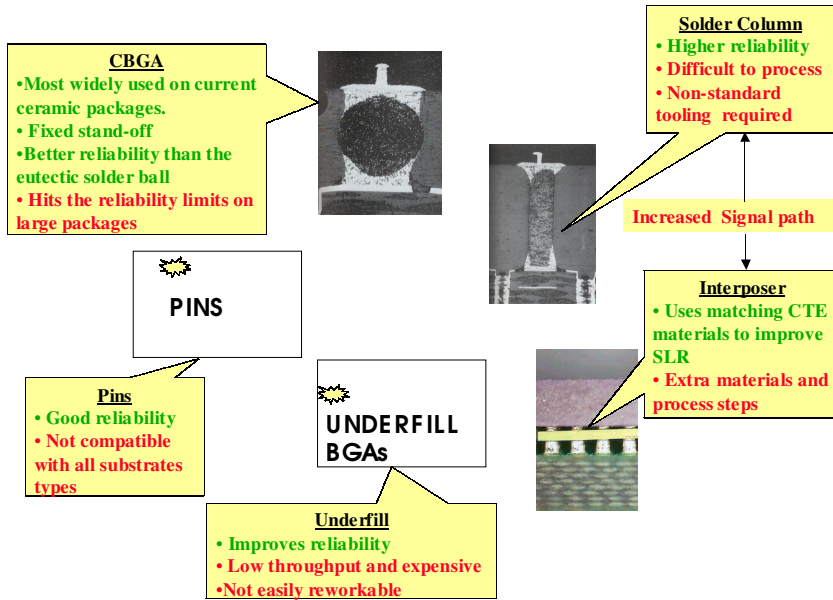
As shown in Figure 1, increases in the substrate size (DNP), and the difference in coefficients of expansion ($\Delta \alpha$) increases the shear strain, which decreases mechanical reliability. On the other hand increasing the BGA standoff increases the reliability. Hence a bigger BGA ball is considered good for mechanical reliability. But from an electrical performance point of view smaller interconnects are almost always preferable, especially for high-speed digital lines, to minimize the signal losses. There arises the classic dilemma between electrical expectations and mechanical performance. There are numerous options available and which have been tried out to bridge this gap. Some of them being, use of interposers between the substrate and the PCB board, using BGA solder balls with an epoxy like material (underfill) being dispensed to improve reliability. All these options do indeed increase reliability, but these are all extra steps in the process that drastically decrease the throughput and increase cost. Figure 2 shows the various high reliability options with their advantages and drawbacks [2]. So the replacement solution needs to not only have higher reliability, but also needs to be a drop in solution to the existing processes and also have good electrical performance. That brings us to the polymer-coated solder balls.

$$\delta_{ceramic} = DNP \cdot \alpha_{ceramic} \cdot \Delta T$$

$$\delta_{PWB} = DNP \cdot \alpha_{PWB} \cdot \Delta T$$

$$\gamma = \Delta\delta/H$$
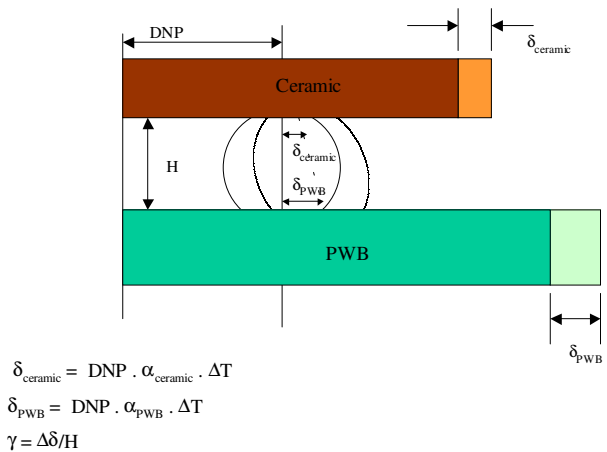
where δ = Relative displacement , DNP = Distance from neutral point, ΔT = Temperature change, α = Coefficient of expansion , γ = Shear strain in the solder and H = Solder standoff height.

Figure 1. Schematic showing the effect of CTE mismatch on solder joint.

Figure 2- Various High Reliability - Second Level Interconnect   Options

CBGA
•Most widely used on current ceramic packages.
• Fixed stand-off
•Better reliability than the eutectic solder ball
• Hits the reliability limits on large packages

Solder Column
• Higher reliability
• Difficult to process
• Non-standard tooling required

Increased Signal path

PINS

UNDERFILL BGAs

Pins
• Good reliability
• Not compatible with all substrates types

Underfill
• Improves reliability
• Low throughput and expensive
•Not easily reworkable

Interposer
• Uses matching CTE materials to improve SLR
• Extra materials and process steps

Solder coated Polymer BGA balls

The polymer core balls (SOL™) are made of a polymer core covered with a thin conductive copper layer and a coating of the solder coating on top of it. The polymer core not only provides a standoff but also acts as a compliant interconnect.

Some of the properties of the polymer core are listed in Table 1.

Young's Modulus	4.8 X 10^3 MPa
Poisson's Ratio	0.38
CTE	40.2 ppm/^{o}C (30 – 60 ^{o}C) 46.2 ppm/^{o}C (60-200 ^{o}C) 46.3 ppm/^{o}C (200 - 280 ^{o}C)
Heat Resistance	Decomposes by heat at 447 ^{o}C

Table 1 Polymer core properties. Courtesy Sekisui Chemical Co. Ltd.

Experimentation

Test Substrate

Ceramic (Alumina) substrates were used in the test. The 2 outer rows of LGA pads were daisy chained. Table 2 shows the details of the ceramic substrate.

Package Size	21 mm
CTE	7 ppm
Thickness	2 mm
I/O Count	400 (Daisy Chained)
BGA Style	Polymer ball attached with eutectic solder paste
Pitch	1mm
Ball Size	0.635 mm

Table 2 - Test Substrate

BGA Assembly Process

BGA placements were done by printing eutectic Sn63/Pb37 solder paste onto LGA pads and then placing either conventional solder balls or the polymer core balls. BGA placements were done using a semi-manual process. The SOL balls are very similar to the conventional solder balls. The only difference is that the polymer core balls are much lighter (Sp. Gravity = 3.6 compared to solder = 7.81) than the conventional solder balls. Custom-made BGA tooling was made to ensure good ball placement on the substrate pads. Parts were then reflowed in a convection oven in a nitrogen atmosphere. A peak temperature of 220°C was selected to ensure that only the eutectic solder paste is reflowed and holds the solder ball in position. As the ball is coated with eutectic (Sn63Pb37) solder paste, the same conditions were used as that would be used for the conventional BGA reflow. Figure 3 shows the cross-section of the 2 types of the BGAs after reflow.
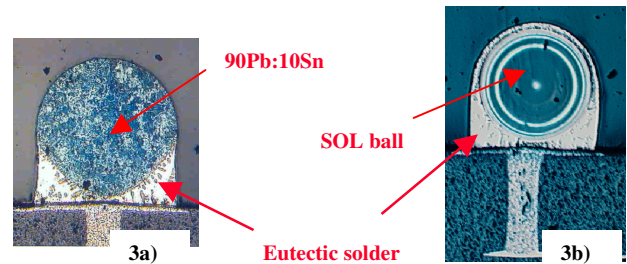

90Pb:10Sn

SOL ball

Eutectic solder

3a)   3b)

Figure 3 - Cross-section of the 3a) conventional BGA and the 3b) Polymer –core BGA.

Board Mount

Several parts were then board mounted on a FR4 printed circuit board. 1 BGA substrate per board was mounted as shown in Figure 4. The FR4 board was designed according to the IPC 9701 standard. Table 3 lists the board properties.

Board Type	FR4
Size	60 X 60 mm
Thickness	62 mils nom.
Cross-Section	6 layers of FR4 and copper with 70% Copper coverage
CTE	14 ppm
Pad Metallization	Solder coated and dielectric defined.

Table 3. PCB Board

Parts were mounted on boards using solder paste. Similar stencil thickness and aperture sizes were used for both board and substrate sides.
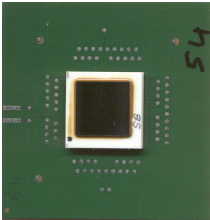
Figure 4 - Board mounted test part

Reliability Testing

The parts were probed for continuity after board mount using a 2-point voltmeter and noted for their initial resistance values. Parts were then temperature cycled in a 2 chamber air-to-air cycling chamber. The temperature conditions were 0-100 °C. Dwell time was 14 mins with 2 mins for transfer. Parts were removed out every 100 cycles and checked for opens. A 20% increase in resistance was considered a failure. No in-situ testing was performed on the parts. Parts were removed from the TCT after 4000 cycles with half the parts using polymer balls with still good.

Results

The cycles to failure were then plotted on a Weibull plot and failure analysis was done on the failed parts. Figure 5 shows the Weibull plot. As seen from the plot, the polymer core solder balls show a 2-3 times increase in reliability at N_{50}.

Failure Analysis

Failure analysis was performed on the failed BGAs. Parts were observed under X-ray and cross-sectioned to look at the failure mode. Figure 6a shows the cross-sections of a failed part for both the conventional. The conventional solder ball failed in the classic failure mode [3]. The crack originates in the eutectic solder close to the interface between either the substrate or the PCB board and the solder ball and propagates all the way in the eutectic material till it fails. Finite element analysis on a similar CBGA model Figure 6b shows the region of high stress corresponds to the actual failure initiation site.

Analysis on the SOL ball shows that even though the high strain region is near the interface of the package and board, the polymer core on the SOL acts as a buffer and relieves the strain. Thus the part withstands high stresses and eventually fails at the weakest region, which is in the middle of the solder coating covering the polymer ball. This solder layer eventually peels off causing the failure as shown in Figure 7. X-rays of the part as shown in Figure 8, show the difference in the failure modes of the conventional CBGA versus the polymer core BGA. As the standoff ball becomes more ductile, it absorbs more strain energy, hence increases the reliability [4]. This explains the higher reliability of the polymer-core BGAs due to its more complaint nature compared to a solder ball.

Data on the polymer core BGAs [5] have shown that increasing the amount of solder to attach the polymer core ball tends to reduce flexibility of the balls and hence reduce their reliability. The correct amount of solder required for optimum reliability needs to be determined.
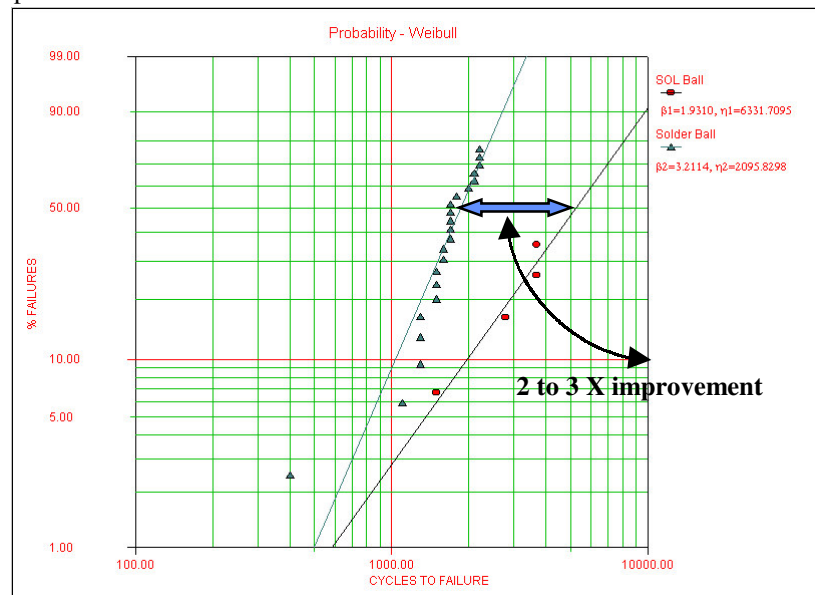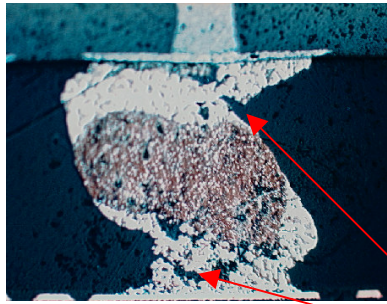
Figure 5 - Weibull plot of parts to failure comparing conventional and plastic –core ball

Crack Initiation Site

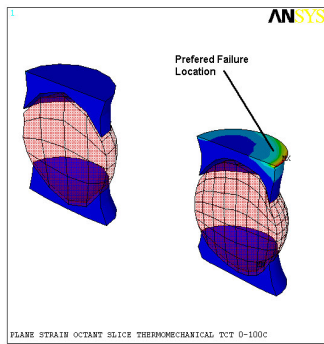**Figure 6a- Conventional CBGA failure**

Figure 6b - Conventional CBGA – High stress region

Ball Shear was performed on the polymer ball and the conventional CBGA using a Dage ball shear machine. There was no big difference in the shear values between the 2 types. The 25 mil conventional CBGA had a shear value of 904 grams whereas the polymer ball had an average shear value of 1000 grams. The failure mode for the conventional BGA is at the high lead ball/eutectic paste interface. Failure for the polymer core ball occurs with the polymer ball rolling off from the copper covering creating a crater of solder. Figure 9 shows the shear surfaces of either type.
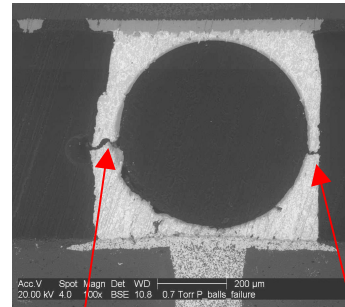

9a   9b
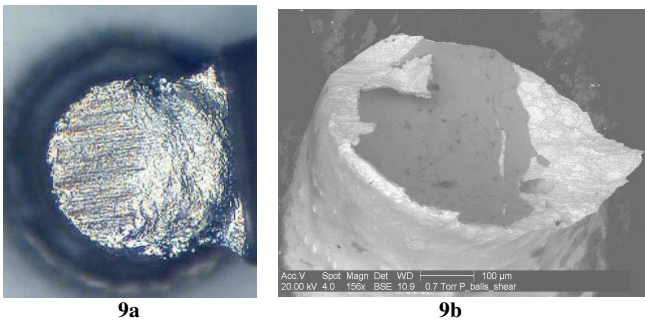
Figure 9 - Ball Shear surfaces of conventional 9a-CBGA and a 9b- polymer core BGA.

Typical failure location on a plastic-core BGA

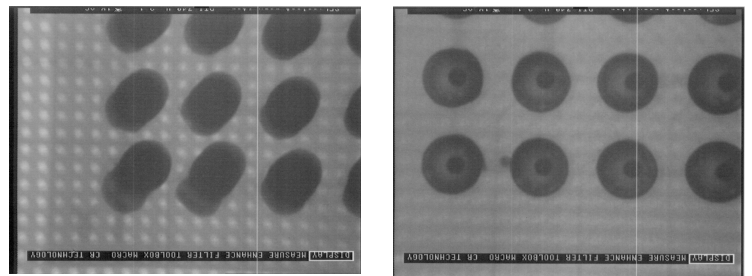**Figure 7 - Failure mode – Polymer –core BGA**

Figure 8 - X-rays showing difference in failure mode between the conventional and Polymer core BGAs

Electrical Simulation

A simple straightforward DC resistance analysis and a full-wave electromagnetic RF simulation were performed to characterize the electrical performance of the polymer core ball. Even as the failure analysis of the preceding sections indicates that the polymer core balls have considerable advantage in second-level reliability over conventional solid Pb90/10Sn solder balls, it is important to understand the electrical tradeoffs, if any that might arise from using the SOL balls. Because of the increased mechanical robustness of the SOL over conventional solder balls, smaller ball diameters, which are preferred in electrical high-speed digital applications, can be used in BGA packages. However, for the purposes of the electrical analysis, a one-to-one comparison is made between balls of equal diameters for the SOL and the conventional solder ball.

DC Analysis

Figure 10 illustrates the geometries used for the DC resistance analysis. The SOL is modeled as concentric cylinders of Sn63/Pb37 solder, pure copper, and a polymer core. Typical Sn63/Pb37 solder thicknesses for the SOL are 20 um. The conventional ball is modeled as a cylinder of solid Sn90/Pb10 solder having a diameter equal to the SOL ball. For the typical Sn63/Pb37 solder thickness and a given ball diameter, DC analysis can determine the required copper thickness that leads to a ball resistance which has equal resistance to that of a conventional solid solder ball. Table 4 shows the required

copper thicknesses for various ball dimensions. These required copper thickness are close to typical values used in the SOL balls. From a DC resistance point of view, there is virtually no degradation in electrical performance from the polymer-core balls.
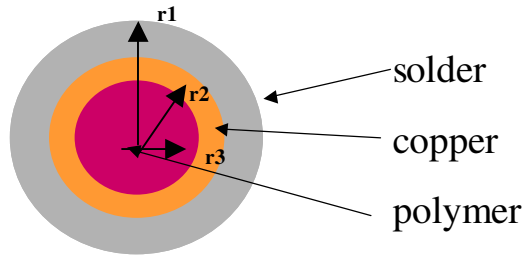

Figure 10 - Model - DC resistance for polymer/copper/solder (90/10)

Ball Diameter 2*r1 (mils)	Copper thickness (r2-r3) (μ)	Actual Copper thickness (μ)	Difference in resistance mΩ
16	7.66		
18	8.73		
20	9.79	6	0.25
22	10.85		
24	11.91		
25	12.44	8	0.19
26	12.97		
28	14.04		

Table 4 - Required copper thickness for a given ball diameter having 20 um of solder thickness

RF Performance Comparison [6], [7]

To investigate the RF performance of the polymer core ball, a full-wave electromagnetic model of a high-speed BGA package transition was used. This RF transition is shown in Figure 11.
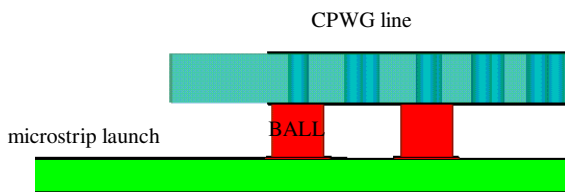

Figure 11 - CST BGA Model: Hi-Speed transitions

A signal to a CPWG transmission line on a ceramic BGA package is launched from a microstrip on a Rogers 6002 board through a ball transition. The package balls are modeled as cylinders that are 16 mils in diameter and 16 mils in height. For the SOL model, the copper thickness is 8 um with a conductivity of 5.81E7 mho/m. The solid solder ball model has the same ball dimensions and a conductivity of 4.77E6 mho/m. The model was simulated in Computer Simulation Technology's Microwave Studio. As is well known from microwave theory, the skin effect associated with high frequency electrical signals and the copper of the SOL should combine to provide good electrical performance. Figure 12 shows a comparison of insertion loss between using an SOL ball and a conventional solder ball. As can be seen, there is virtually no difference in the curves.
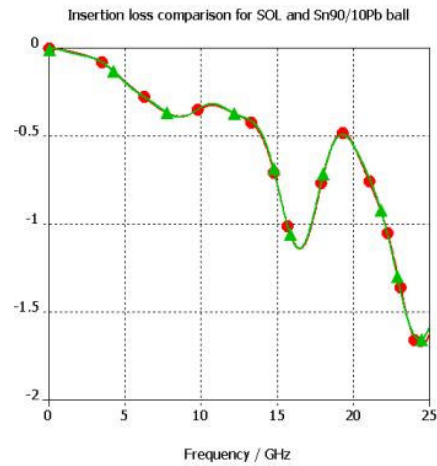

Figure 12 - Insertion loss comparison

Conclusion

- In a rare occurrence in the electronic packaging world, a technology that improves mechanical robustness without impact to electrical performance has been demonstrated. In practical implementation, the polymer-core BGA can even provide improved electrical performance by making the use of smaller diameter balls available to high-speed digital packages.

- SOL Balls demonstrates 2 to 3 times of increase in second level reliability when compared to conventional CBGA. The polymer core of the SOL ball acting as a compliant stress buffer is the critical difference between a conventional CBGA and a polymer core BGA.

- Assembly process can be implemented without any major process change or new equipment set thus creating a drop in solution.

- Provides a potential for high reliability lead-free solution.

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