

Bend Testing Direct Chip Attach Bump Architectures with Stress Mode Correlated to Field-Wearout in Handheld Applications

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Abstract

Our previous work demonstrated a field wearout mechanism in direct-chip-attach Chip Scale Package (CSP) electronic assemblies correlated to low-strain, high cycle multiaxial stresses associated with PC board bending. This multiaxial stress mechanism is not activated by traditional thermal cycling tests, but can be reproduced by subjecting test boards to high cycle deflection with a custom test fixture. We dub our custom test apparatus "MultiFlexer", designed to rapidly stress daisy chain test boards thus providing rapid and low-cost feedback on possible new bump-attachment architectures. We show example bending performance from single- and multi-layer BCB, and polymer-collar-based bump architectures. Clearly superior lifetime performance of the single BCB polymer collar design is made more apparent by the fact that the polymer collar devices did not exhibit a through-solder failure mechanism, but even outlasted the flexible multilayer build-up PC board they were mounted upon.

Key words: CSP, chip scale package, direct chip attach, four-point bend, solder joint reliability, cyclic bend testing

Introduction

Our prior work utilized board bending approaches to augment classical temperature cycling in order to examine the relative durability of various CSP process architectures. This paper represents the last of our efforts to characterize differences between architectures that place compliant polymers between the bump and silicon ("narrow via"), versus UBM placed directly over the chip passivation ("wide via") versus the polymer collar developed by Flip Chip International.

Background— Bending Complimenting Temperature Cycling Approaches

Temperature Cycling (TC) approaches [1] are commonly used for testing Chip Scale Packages, a typical profile being 125 degrees centigrade to -40 degrees centigrade consisting of 15 minute ramps and dwells. As failure results were analyzed, we questioned the validity of this TC test when trying to qualify packages going into hand-held applications: Some early devices which passed simple TC tests

were "falling off the board" after mechanical handling, and other devices manifested an unusual early life failure mechanism. These observations led into an initial testing phase with a crude mechanical bending technique [2], enabling the collection of representative failure data much more quickly. More equipment design work followed [3] to develop a test fixture in an attempt to produce more consistent results.

There were also efforts to optimize the board design for compatibility with long-term bump reliability [4]. This was intended to discover any latent process weaknesses when applying a range of multiaxial stresses. The finding of infant mortality failures related to pre-bending was suggestive of the need for improved process and/or architecture approaches. However, there were also board-level failures above some threshold board stress (catastrophic board failures), as well as bump-level crack propagation consistent with bending fatigue seen in field wearout (cell phones with devices mounted opposite the key pad):

A popular cell phone was subjected to normal field use for approximately one year, then taken apart for evaluation prior to failure. One of the points of observation was to characterize the effects of locating the CSP's directly opposite the keypad. Figure 1 illustrates an observational cross-section through such a CSP device [5].

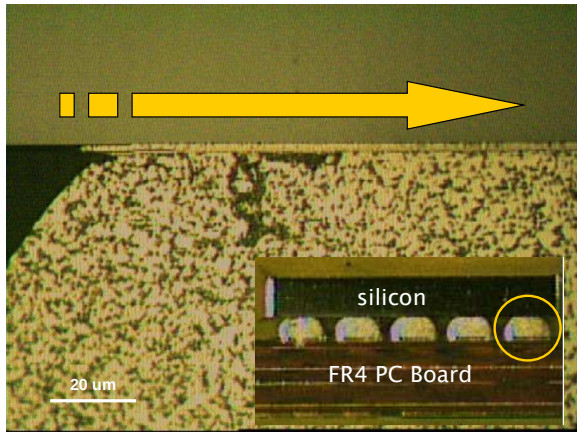


Figure 1: Crack found after one year use in cell phone application. Although the crack does not propagate completely through the solder ball, and difficult to see here, the crack is typical of those found after cyclic board bend testing. Crack propagation is through solder ball near silicon, crack initiates at the “inner” edge and progresses outward (arrow) [5]. Note here that there is no sign of thermally activated domain coarsening, typical of TC testing.

Figure 2 indicates the desired type and location of cracking that results from such an architecture exhibiting classical shear fatigue, having undergone temperature cycling. Note the coalescence of primary lead and tin domains that precede the initiation and propagation of the actual crack, as per Lau [6].

It is clear from a comparison of the two bumps in equivalent array position (Figure 2, versus Figure 1) that stresses produced during thermal cycling are not the same as those produced during normal wear in a handheld application [5]. The device from the cell phone exhibits no domain coarsening, however, the crack still propagates along the upper section of the solder bump. The TC-induced crack begins at the outer edge and propagates inward, while the bending-induced crack initiates at the inner edge of the ball and propagates to the outside—simultaneously with the propagation of a crack at the PCB side of the ball, beginning at the outside of the bump moving in.

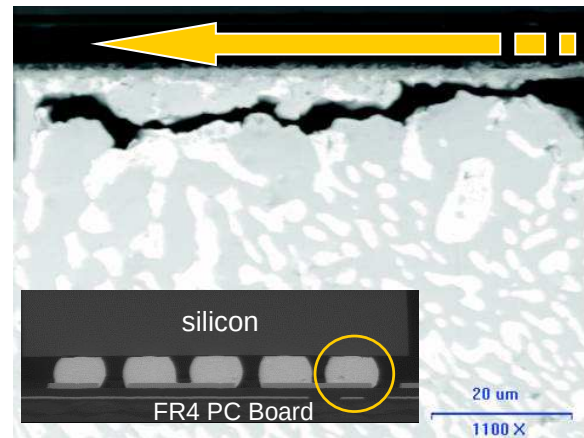


Figure 2: Crack in solder ball near silicon die resulting from temperature cycling. Crack initiates at the “outer” edge and progresses inward (arrow), also note the coarsening of the primary lead/tin domains.

Experimental Objectives—Comparing Architectures

This paper looks at four architectural layouts for bump attachment. The main distinction to note in the naming scheme is Wide Via versus Narrow Via. The Narrow Via parts use a standard (redistributed) I/O pad, but utilize the barrier and planarizing properties of the first BCB layer to further isolate the solder bump from circuitry in the area between the pad edge, and the edge of the bump. A schematic of the Narrow Via part is shown in Figure 3. Note from prior efforts [3] in BHT testing that this layer is important to electronically isolate the passivation nitride (with high pinhole density) from the UBM.

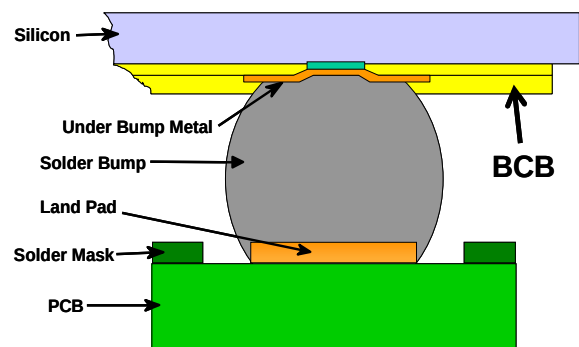


Figure 3: Schematic of the Narrow Via bump architecture, showing I/O pad, BCB layers, and placement of under bump metallurgy. BCB extends under the bump to the edge of the pad as a cushion and dielectric layer.

The Wide Via parts use a standard I/O pad with the first layer of BCB widened out to allow UBM directly in contact with the passivation nitride.

A schematic of the Wide Via part is shown in Figure 4. This architecture is inherently laden with nascent passivation defects and can give rise to the IC-UBM shorting, with high topography.

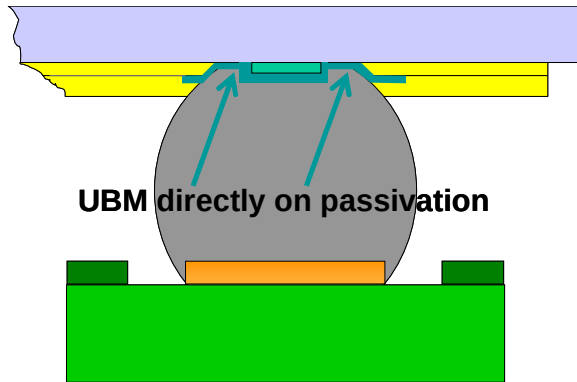


Figure 4: Schematic of the Wide Via bump architecture, showing widened BCB openings to allow UBM in direct contact with the passivation layer.

Another variation in architecture was a Narrow Via device with polymer collar support structure forming a bond around the base of the solder ball to the BCB layer. Figure 5 shows a schematic of the polymer collar architecture used by Flip Chip International [7], note here the schematic is flipped over from the others, showing the silicon at the bottom (PCB is not illustrated).

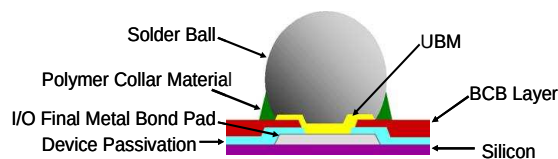


Figure 5: Schematic of the Polymer Collar device architecture (courtesy of Flip Chip International).

Table 1 summarizes the architectures compared in this paper: Cost-saving process architectures were studied in single-BCB (TC and Bending). Reliability improvements were studied in the “collar” technology created by Flip Chip International [8]. Wide via and narrow via splits were included as reference. The leftmost column contains the code, or abbreviated nomenclature, used during testing to distinguish between splits. All splits listed were subjected to TC and Bending. Lead-free splits were scrapped in process.

Figure 6 illustrates results from the TC testing, summarized as cumulative failures over temperature cycles completed. The four architectures are: Narrow Via with single BCB [9], Narrow Via

with single BCB and polymer collar [8], Narrow Via with dual BCB, and Wide Via with dual BCB. The test device with the polymer collar had one failure after 1379 temperature cycles, at which time the test was terminated.

Table 1– Summary of splits reported in this study.

Code	Split	Objective
N2XSE	Narrow via / dual BCB / no collar / standard eutectic	Current STD
N1XSE	Narrow via / single BCB / no collar / standard eutectic	Lower cost target
N1CSE	Narrow via / single BCB / collar / standard eutectic	Improved reliability vs. single BCB variant
W2XSE	Wide via / dual BCB / no collar / standard eutectic	Compare barrier effectiveness relative to BCB

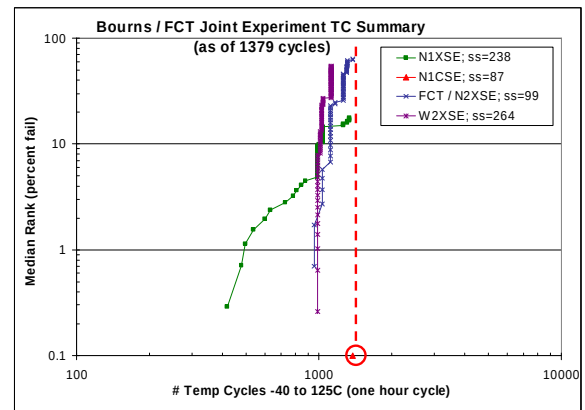


Figure 6: Temperature cycle cumulative failure occurrence results from different architectural splits. The test was terminated at 1379 cycles (shown by dashed line) after the first Narrow Via single BCB and polymer collar failure (circled).

Bending is done with 5x5 ball, 0.5mm pitch array devices mounted on exclusively microvia-in-pad boards so that uniformity of solder fillet shape and standoff height can be achieved [10,11]. The eight layer build-up for this microvia-in-pad board is detailed in Figure 7. Diagnostic probe points in the board (Figure 8) allow each bump pair to be independently probed for continuity when the board has failed during mechanical testing. This is critical for isolating the bump that caused the failure in real time.

Layer		THICKNESS (mils)
1	Base Copper plus plating	1.10 +/- 0.3
	Resin	1.97 +/- 0.4
2	Base Copper plus plating	1.10 +/- 0.3
	prepreg	6.30 +/- 0.8
3	1/2 oz Cu Foil	0.71 +/- 0.3
	Core	6.30 +/- 0.8
4	1/2 oz Cu Foil	0.71 +/- 0.3
	prepreg	6.30 +/- 0.8
5	1/2 oz Cu Foil	0.71 +/- 0.3
	Core	6.30 +/- 0.8
6	1/2 oz Cu Foil	0.71 +/- 0.3
	prepreg	6.30 +/- 0.8
7	Base Copper plus plating	1.10 +/- 0.3
	Resin	1.97 +/- 0.4
8	Base Copper plus plating	1.10 +/- 0.3
Thickness with plating (Less Soldermask)		42.68 +/- 3.9
LPI Soldermask 2X		1.22
Total Thickness		43.90 +/- 3.9

Figure 7: Illustration for multi-Layer build-up construction of microvia-in-pad mechanical test board.

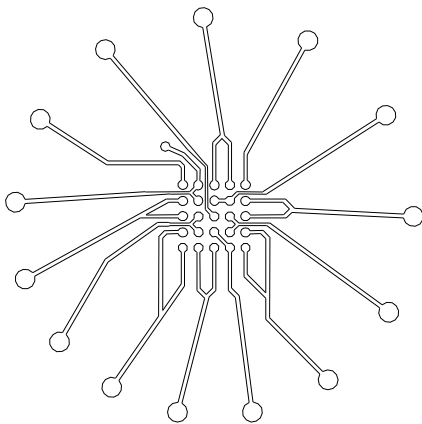


Figure 8: Test board probe points for isolating failed solder bump within array. Diagnostic probe points allow each bump pair to be independently probed for continuity when the board has failed during mechanical testing.

Experimental Discussion

Testing Approach

The test boards hold 100 parts enabling reasonable populations to be sampled. Boards are flexed using a four-point bend creating an even strain rate distribution across the entire board for the same period of time (verified using strain gages). In the event of a failure, testing is halted and thorough documentation of the failure is made along with cross-section images of select failure sites. These failures are grouped using Weibull analysis techniques.

Test Configuration

The MultFlex bend test system was designed to utilize a four-point bend approach (see Figure 9). The test board is placed into the fixture, testing is started and the resistance through the daisy-chained devices is continuously monitored by a source meter. The source meter is programmed to trigger an 'open' event if there is a 10X magnitude increase in board resistance (signifying a part has failed and one or more interconnects are electrically open). Testing automatically halts at this point.

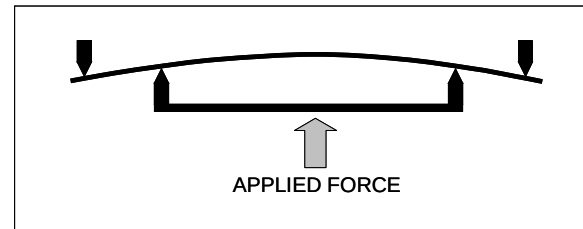


Figure 9: Rough illustration showing the four-point bend methodology used on the MultiFlexer. The key attribute of this configuration is that homogenous stress states are imposed in the board positions located inside the two inner force application points.

Figure 10 is a photograph of the four-point fixture portion of the MultiFlexer with test board inserted and at rest position. The contacts are made from Teflon[®] providing a rigid contact, but self lubricating for smooth, low friction operation against the PCB. Rare earth composite (Neodymium-Iron-Boron) magnets were embedded into the contacts, opposing other cylindrical rare earth magnets aligned with them on the top and bottom of the test board.

Without the magnets in place, the test board experiences "slap" operating at five hertz, because the board inertia created a momentary separation relative to the Teflon[®] contacts. This slap was violent enough to cause shock, measurable with surface mounted strain gages—a very adverse effect when targeting mechanical bending failures only. With magnets in place, no slap was evident, as measured by smooth strain response profile (lack of incongruous or discontinuous strain excursions - see Figure 11).

The closed loop system inputs a waveform of known amplitude and frequency. The waveform signal feeds a linear amplifier. The linear amplifier drives the electrodynamic transducer with the attached inner four-point stage. The force applied is measured by a load cell, and the board deflection is read (near the center) by a laser displacement sensor.

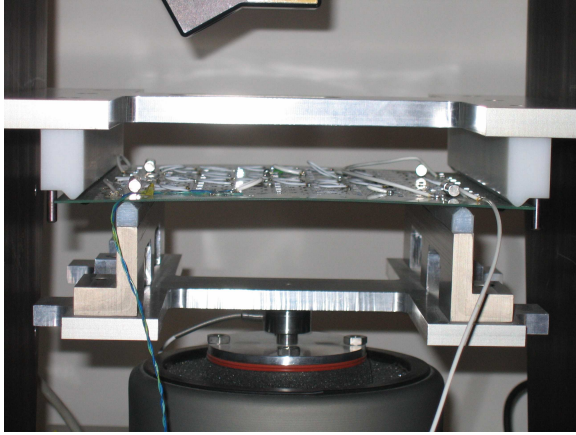


Figure 10: Photograph showing the MultiFlexer four-point bend fixture with test board inserted. Cylinders above the inner force application points are magnets used to prevent board “slap” at the peak displacement. There are also magnets positioned below the board under the outer application points, however they are not visible in this photograph.

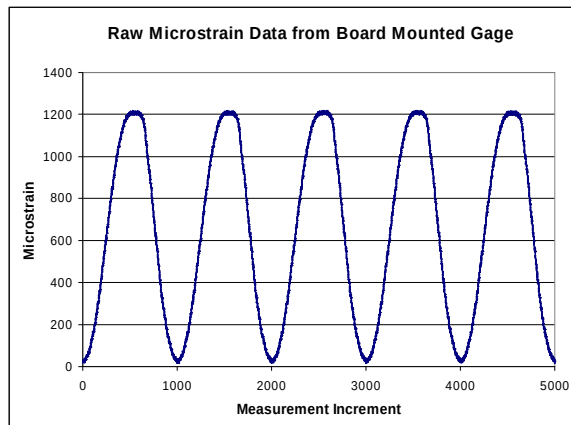


Figure 11: Strain response profile as read directly by surface mounted strain gage. Testing set at 5Hz with sinusoidal waveform.

A screen capture for the custom LabVIEW[®] front panel is shown in Figure 12. The program is very flexible to allow for different waveforms on the input as desired, and each waveform can be dialed in for matching specified requirements.

Each output is monitored “real time” by the same LabVIEW[®] program and saved at specified intervals for minimum and maximum values reached during one cycle. There is great flexibility in the software for output signals. Any type of strain gage can be used, fail-safes can be added for each signal, and scales can be adjusted on-the-fly. Both digital and analog signals are possible, with results projected to the front panel for quick reference.

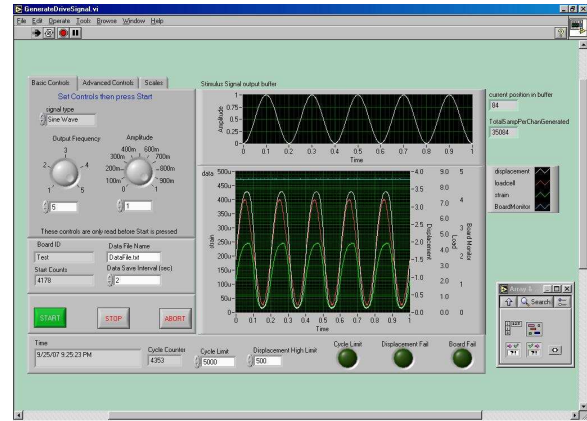


Figure 12: Screen capture showing front panel for the custom LabVIEW[®] program running the MultiFlexer.

Testing and Board Requirements

For the cyclic mechanical bending approach to be successful, it is believed that the following must be considered:

- Large sample size (e.g., 100 pcs per board) tested simultaneously for obtaining mechanistic data.
- Constant bend radius of curvature experienced by each device under test.
- Constant time under stress for each device tested.
- Continuous electrical monitoring.
- Force calibration technique (closed loop feedback vs. one-time set-up).
- Considerations for distinguishing device open vs. board failure--
 - board deflection beyond threshold (assumes constant force) -or-
 - reduction of applied force below minimum threshold (assumes constant deflection)
- Nonconveyance of bending moment from support structure or friction (see [12]).
- Loading characteristic (waveform shape).
- Return to relaxed position upon failure detection.
- Minimization of vibrational harmonics during bend cycle.

Each test board has a minimum of one strain gage mounted on the device side. This strain gage reading is crucial to the success of the test, because it serves as a means to ensure consistent test conditions from board to board. Strain gage readings are also used to verify proper board strain anytime a test is restarted (i.e., after removal and replacement of the test board when probing for failures).

It is important to note again, the strain gages are mounted at board level and all failure analysis work is correlated to that strain level. It was possible to target the correct strain level, as it had been

determined from previous bending experimentation. This previous work [2, 13] documents how critical it is to stay within the elastic response regime of the PCB; pass beyond this and multiple premature board level failure mechanisms will arise.

Results

Using the same data analysis methodology as with the TC testing, all failures under mechanical bend testing were tabulated by architecture, and Weibull techniques were used to evaluate the data. Figure 13 contains the Weibull plot of the four splits run on the MultiFlexer. It can be seen that the Narrow Via dual BCB and Wide Via had comparable results. The Narrow Via single BCB performed very well, and after 15.3 million cycles the similar device with the polymer collar had only three failures.

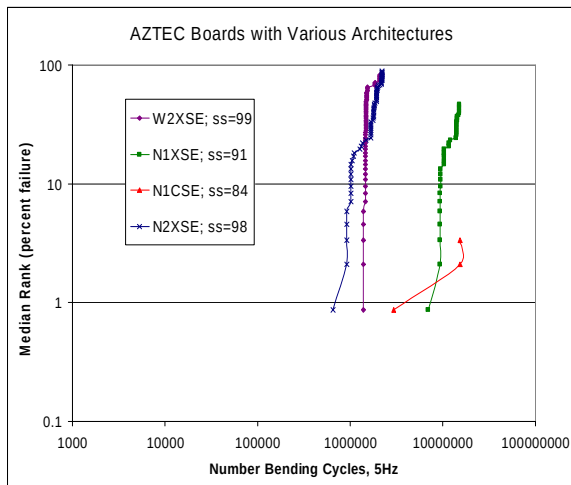


Figure 13: Cyclic Bend Testing results from several splits. Boards are tested individually, after 15.3 million cycles and three failures, testing was terminated on the Narrow Via single BCB and polymer collar device.

The Weibull plots alone cannot tell the whole story, we need the assistance of physical failure analysis in order to determine if the failure mechanism represents an optimized “wearout” mechanism, versus a nascent weakness in the process architecture. Looking at the cross-sections, Figure 14 illustrates the typical wearout failure mode under low-level elastic strain, mechanical cycling. Figure 15 is a magnified view of Figure 14 (shown by the square outline). Notice the lack of domain coarsening in the vicinity of the crack typical of mechanical action *sans* thermal activation, and the line of propagation for the crack is at the top of the solder bump, and along the under-bump metallurgy (UBM) interface to the solder bump.

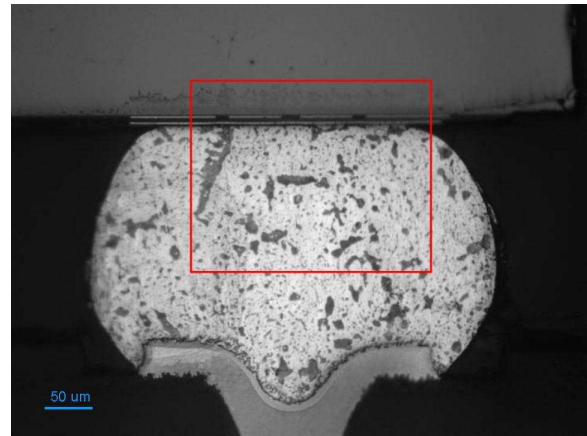


Figure 14: Failed solder bump (electronically open) where the crack propagates across the top near the UBM interface, a typical failure observed in Narrow Via splits, single or dual BCB.

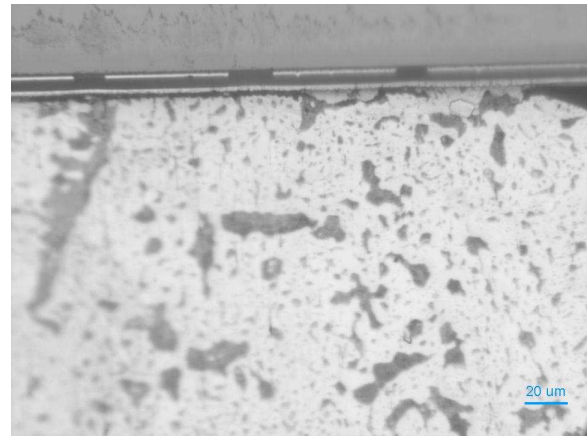


Figure 15: Closer view of figure 14 (indicated by box) showing failure mechanism. This is a Narrow Via dual BCB part.

Figure 15 is also typical of the failure mechanism seen with the Narrow Via dual BCB architecture during current testing. Figure 16 gives an example of a Narrow Via single BCB failure. Although there is clear shift in performance between the dual and single BCB Narrow Via devices from Figure 13, failure analysis of cross-sections shows the active mechanisms to be equivalent.

Examining Figures 15 and 16, both show the crack appears to prefer the UBM-to-solder interface, possibly indicating poor bonding to the part with formation of intermetallic compounds. This is representative of all Narrow Via parts with the exception of the split using a polymer collar.

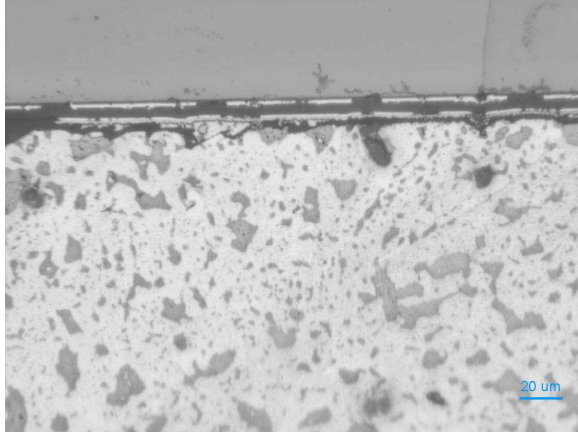


Figure 16: Crack propagation along the UBM-to-solder interface. This is a Narrow Via single BCB part.

The Wide Via architecture exhibited crack propagation through the solder only. This can be seen from cross-section in Figure 17. Notice the crack does not appear to be drawn to the very top of the solder bump or the UBM interface, indicative of good bonding to the part. This micrograph is representative of all the Wide Via parts examined within the split.

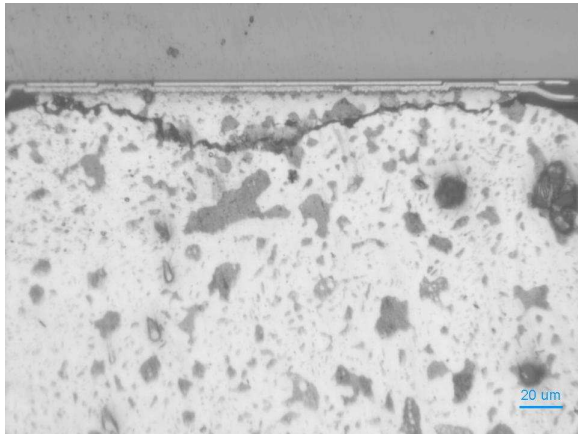


Figure 17: Typical crack propagation found with cross-sections of all Wide Via parts under current testing.

A very different failure mechanism was found when closely examining the Narrow Via single BCB devices with polymer collars. This architecture did not exhibit any classical wearout failure mechanism through the solder bump, but rather a fatigue crack through the PC-board copper trace (see Figure 18) after close to 15 million bending cycles.

This suggests that the lifetime performance of the solder joint is superior to that of the board and is indeed improved with this architectural variant. One may conclude with the polymer collar, the

devices now outlast the board when tested under low-level strain, high-cycle mechanical bending.

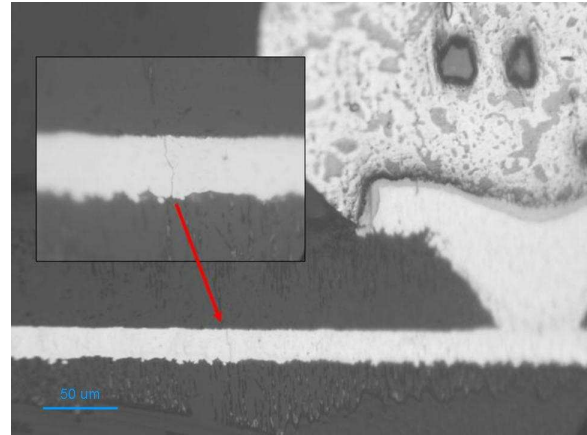


Figure 18: Failure mechanism observed with the architecture utilizing the polymer collar. Inset micrograph is a magnification of the crack through the copper trace, representative of all devices.

Although the failure mechanisms for the polymer collar device were different in TC versus bending, this device outperformed all others in each test, as illustrated in both figures 6 and 13. TC testing results have all devices, other than the polymer collar, closely grouped together (see Figure 6). Bending spreads the results out more (see Figure 13), allowing for an easier ranking based on lifetime to failure.

Discussion

Four different CSP architectures were evaluated through a series of tests, beginning with temperature cycling and low-level strain, high-cycle mechanical bending. We know that TC predominantly imposes shear stress, so the bending would be expected to produce different results, because multiaxial forces are in play. Direct comparison of the two test approaches is verification that the bend test is useful in collecting statistically significant data on long-term reliability in a real field application. Looking at the Figure 6 results of TC data, while the same shear mechanism (Figure 2) is observed with all splits, there are different slope characteristics for each. However, the Figure 13 bending data yields similar slope characteristics but different failure mechanisms were active (as can be observed in Figures 15 thru 18).

While bending rapidly produces multiaxial forces with low-cost results, TC is relatively slow, expensive and not representative of field conditions (bending, dropping).

Conclusion

It is well understood that TC testing stresses system CTE mismatch to evaluate reliability. Breaking the package down into three basic components gives: PC Board, solder bump, and silicon die. Considering the largest CTE mismatch is between the silicon die and the PCB, it can be concluded the predominant shear stress felt by the solder bump is uniaxial in nature (side-to-side).

Bending produces multiaxial stresses within the system. As the semi-compliant board is flexed, the silicon die is rigid and resists deformation. Stresses reside within the solder bump or the interface between solder bump and UBM. The polymer collar implementation helps to redistribute the stresses back into the board.

While the crack found in real world application (actual device used in cell phone) does not correlate well to temperature cycling, this failure mechanism does correlate well to cyclic bend testing results. It can be concluded then that bend testing direct chip attach bump architectures yields stress modes correlated to field-wearout in handheld applications.

Acknowledgments

David Turner for designing the chip and 100 pc daisy chain boards; for helpful assistance debugging various setups and making them work. Steven Aposhian of National Instruments for writing the LabVIEW[®] code and designing the software interface for the test program. Kent Jensen and Randy Guss for board assembly assistance. Jeff Buttler and Brent Porter for designing and manufacturing the components needed to assemble and operate the bend testing apparatus. Scott Barrett and Flip Chip International for production of bump splits on experimental wafers. Mitsuaki Toda, Henry Izawa and JVC for assistance in planning and building all test boards. Aaron Smith and Fairchild Semiconductor for use of failure analysis lab polishers, polishing supplies, and use of microscopy and imaging equipment is gratefully appreciated.

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