Failure Analysis of BGAs

Ed Hare, Ph.D. – February 21, 2007

Introduction

Failure analysis of BGA devices can be both expensive and daunting. The primary advantage of BGA packaging is the packing of large numbers, 400-500+, of I/O pins into a relatively small area. The high number of I/O is also what makes the failure analysis task so complex.

This document attempts to describe several BGA failure modes and analysis approaches that can be performed with a limited number of analytical tools (e.g. DMM, microsectioning, and SEM/EDS). The document also describes a number of other more advanced approaches where the limited tools are not enough to identify the failure cause.

BGA Failure Modes

There have been a number of BGA failure modes identified in this laboratory that are discussed below.

Black Pad Syndrome (BPS)

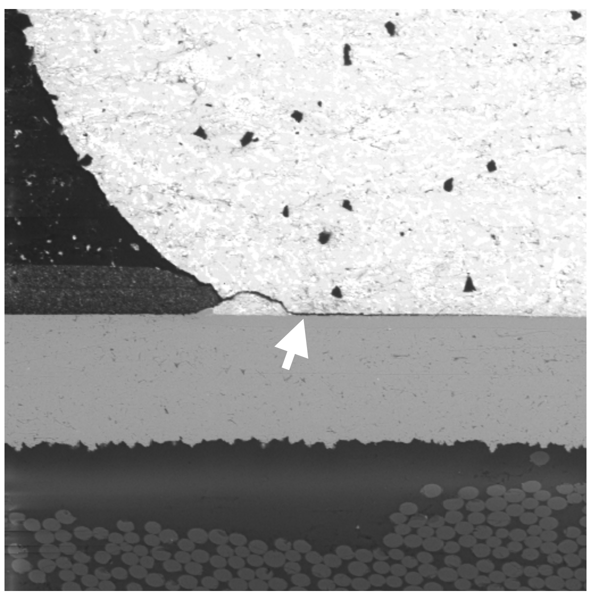

Figure 1 - Microsection of partially fracture BGA solder joint [362X, BSE SEM image, ref. SLI-465].

"Black Pad Syndrome" has been described by a number of authors [1 – 5]. The failure mechanism is uniquely related to electroless-nickel immersion-gold (ENIG) finished printed-wiring-boards. The phenomenon is related to concentration of phosphorus at the EN/IG interface in the Ni-P alloy (EN layer) during the IG deposition. The IG bath is corrosive with respect to Ni-P such that Ni dissolves into the IG bath leaving behind phosphorus. The P-rich layer at the EN/IG interface retards the normal wetting process of solder to the EN layer during solder reflow. This creates a "weak" interface that is subject to failure due to thermal stresses (warpage), mechanical loading (bending), or shock loading (drop).

"Black Pad Syndrome" is sometimes referred to as "Dark Line Defect" most likely because the P-rich layer appears dark in BSE SEM images of solder joint microsections (e.g. Fig. 1). The P-rich layer appears dark in these images because of the low atomic number of phosphorous (Z = 15), which makes it less efficient at backscattering electrons than nickel (Z = 28). The base phosphorous concentration in electroless-nickel is typically 7 – 9 wt%. The phosphorous concentration in the P-rich layer can be as high as 30 wt%. Fig. 2 shows a fracture surface of a BGA solder joint that shows "hyper-etching" of the EG grain boundaries, which is a characteristic of BPS. The concentration of phosphorous at the surface was measured as ~ 28 wt% based on EDS spectra. The BGA solder joint lifted cleanly along with the Ni-Sn intermetallic compound layer off of the underlying pad leaving only the P-rich EN that is characteristic of BPS.

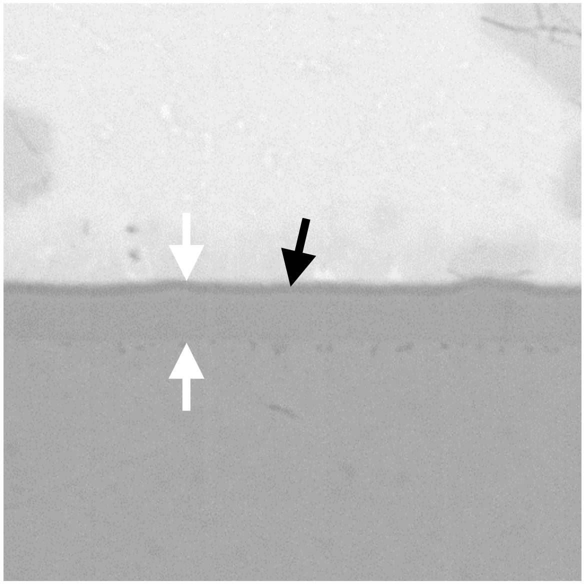

Figure 2 - "Dark line defect" in Pb-free BGA solder joint microsection [2549X, BSE SEM image, ref. SLI-1393]

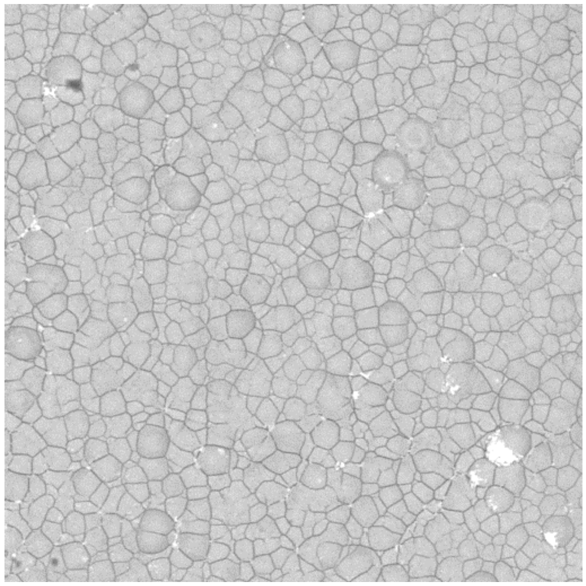

Figure 3 – BGA fracture surface showing "Hyper-etched" EN [852X, BSE SEM image, ref. SLI-983]. The phosphorous concentration at the surface was ~ 28 wt% based on EDS data.

BPS is not limited to BGA components, but it is most often identified initially because of assembly level BGA failures due to the exaggerated stress levels on BGA solder joints (i.e. by comparison to leaded devices such as quad-flat-packs). BGAs are similar to leadless-chip-carriers in that they have no leads to buffer stresses to the solder joints. They also tend to have larger thermal coefficient of expansion (TCE) mismatches with the PWB than other plastic molded components because of relatively large die sizes, which leads to warpage stresses in the BGA solder joints.

Brittle Fracture Other than BPS

Brittle fracture can occur at PWB or BGA substrate pad interfaces even in the absence of BPS. The example shown in Fig. 4 shows brittle fracture that was most likely caused by mechanical shock (i.e. drop). The reason for this is that even if the interface isn't weakened by a mechanism such as BPS the ball/pad interface can be the "weakest link" when high enough strain rates are involved that strain relief due to creep in the bulk solder is not possible.

There are other mechanisms that can play a role in apparent brittle fractures such as micro-voids at the ball PWB interface [6]. There are also cases where residues (such as solder mask) are left on the pads in small enough amounts that the ball attachment or soldering process to the PWB is not grossly affected, but nevertheless the interface is weakened due to the contamination.

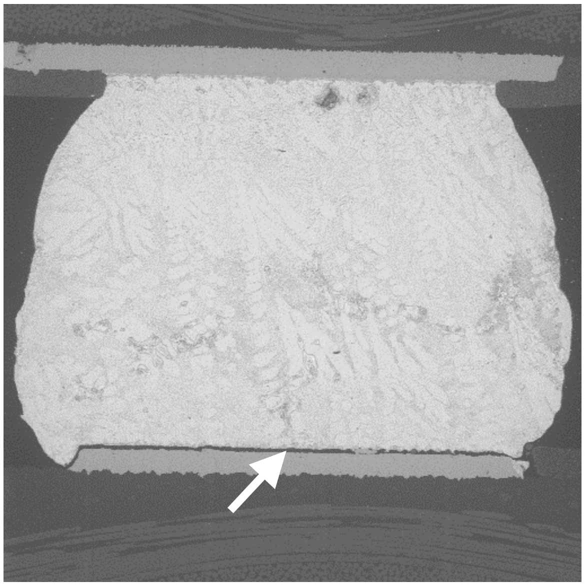

Figure 4 - Brittle failure of Pb-free BGA solder joint at PWB/ball interface [92X, BSE SEM image, ref. SLI-1283].

Die Cracking

Die cracking is illustrated on Fig. 5. This BGA is one of several failed devices where the failure was detected at elevated temperature testing. The device was actually functional at room temperature because the crack path missed the active device area. The crack was most likely due to bending stresses caused by thermal expansion mismatch or mechanical bending.

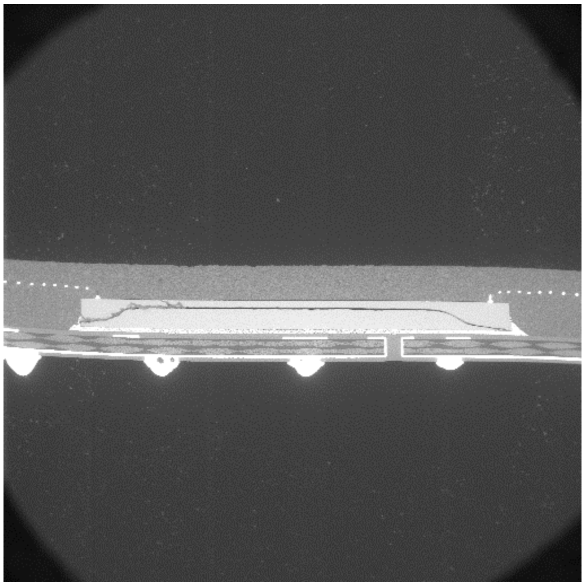

Figure 5 - BGA section showing die crack [13X, BSE SEM image, ref. SLI-1345].

Die Level Faults

Figures 6 & 7 show a die level fault on a BGA where device power was shorted to device ground. The damage appeared to have been caused either by inadvertent mechanical contact with the die surface or possible due to injection stresses molding that exceeded the strength of the die passivation layer.

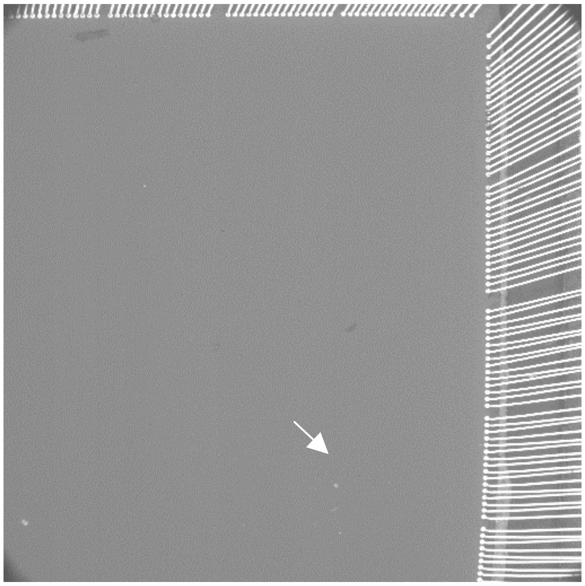

Figure 6 - Decapsulated BGA showing location of short at die level [14X, BSE SEM image, ref. SLI-1301].

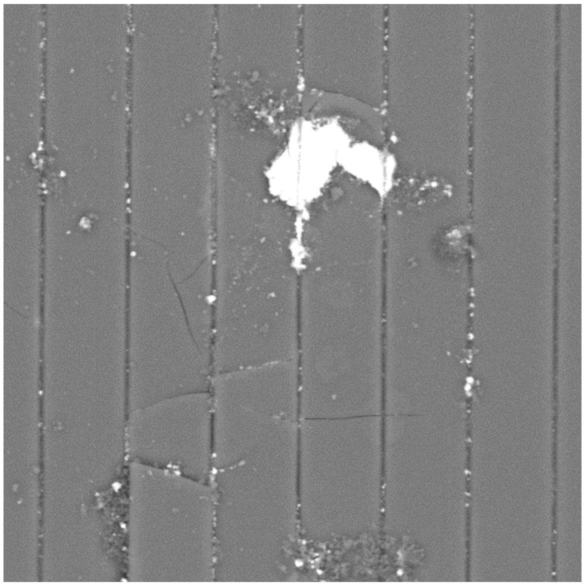

Figure 7 – Short site on the BGA die from Fig. 6 [683X, BSE SEM image, ref. SLI-1301].

Warpage Issues

Warpage due to TCE mismatch between the BGA package and the PWB can cause die cracks (e.g. Fig. 5). When the warpage is extreme during reflow it can cause insufficient contact of the ball with the solder paste for wetting and normal solder joint formation (e.g. Fig. 2).

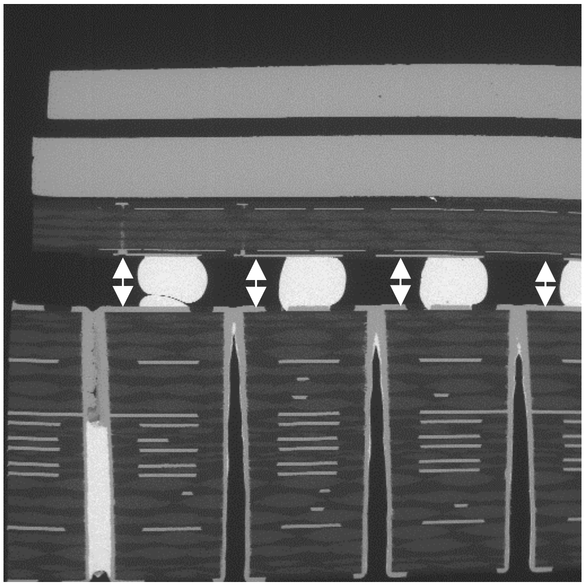

Figure 8 - Warpage related solder joint open at corner ball [16X, BSE SEM image, ref. SLI-1044]. The residual warpage was measured as 27%.

Solder Reflow Issues

Solder voiding is a frequently reported problem for BGA solder reflow. Fig. 9 shows a case where the voids appeared to be the primary factor in separation of the ball from the BGA substrate pad during "drop" testing of a hand-held electronic device. The voids entrapped flux and may suggest that an inadequate reflow profile (i.e. time-temperature profile) was used during board level assembly. The large thermal mass associated with BGAs can lead to reflow problems as the BGAs tend to lag most of the other components on the assembly in terms of peak temperature during reflow.

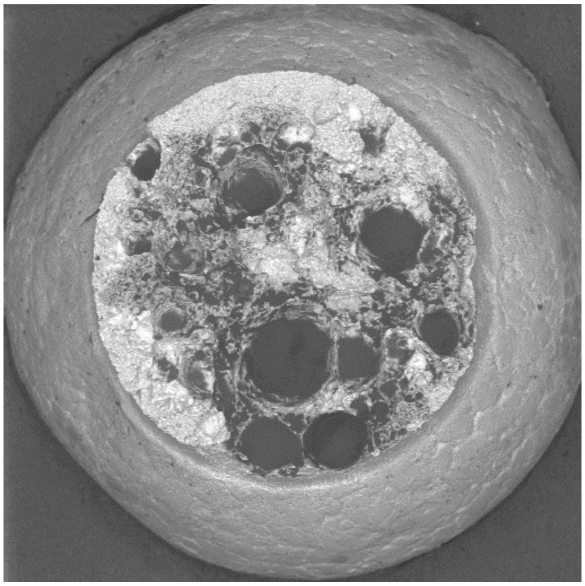

Figure 9 - BGA solder joint fracture surface with flux entrapment [137X, BSE SEM image, ref. SLI-882]. This solder joint failed at the BGA substrate/ball interface during a drop test in a hand-held electronic device.

Failure Analysis Considerations

There are a number of factors that should be considered in development of a plan for a particular BGA failure investigation. This is a far more complicated issue than it would be for a failed chip capacitor or transistor. Part of the difficulty is that OEMs tend to have extremely limited capability for diagnosing what actual signals (out of 400+ balls) are involved in a given BGA failure. The level of effort required to do "all that can be done" to diagnose the problem at the assembly level usually precludes that effort. Instead, the device is often simply removed and replaced. This laboratory has received bags full of BGAs that were removed and stored until weeks later when someone decided to address the issue.

It is usually possible to perform some diagnostic testing of the device at the assembly level prior to removing the device from the board. The first step in the BGA failure investigation should be to identify the specific functional fault reported for the assembly and how it implicates the BGA device (i.e. which specific signals are suspect and why). The next step should be to interrogate the PCBA design to see if BGA signals are accessible at test points, PTH vias, connectors, capacitors, etc. If there are accessible signals they should all be tested with respect to device power and ground signals for continuity (which can be done safely using a DMM in diode-test or forward-voltage mode. Additional testing could include operating voltage levels and current draw. This can all be done simultaneously on a "known good" PCBA for direct comparison of measurements.

After exhausting all feasible electrical tests, some consideration should be given to possible non-destructive tests that can be performed at the assembly level. X-ray imaging is non-destructive and can provide helpful information for BGA soldering issues (e.g.

solder bridging, excessive voiding, etc.). CSAM imaging is a non-destructive testing technique that can image delaminations and die cracking associated with package warping and pop-corning of BGAs. If problems are discovered at this stage of the investigation then the assembly can be subjected to destructive analysis such as microsection analysis to verify and determine the physical characteristic of the problem.

One analysis approach that is often suggested for suspected BGA solder joint opens is referred to as “dye and pry”. This is a process of soaking the assembled BGA in a dye under vacuum in order to color any cracks or opening in the solder balls. Then the dye is dried and the package is pried off of the PWB in order to look for existing cracks or flaws. In this laboratory, we utilize a modified approach where we simply pry the device off of the PWB and use a SEM to examine the fractured balls for evidence of PBS, brittle fracture, voiding or other anomalies that might have caused the reported failure. The dye method would obscure this type of analysis due to contamination of the fracture surfaces.

There are occasions when the solder joints are not suspect but rather there is some type of fault internal to the BGA device. In this case, the BGA can be removed from the assembly for further analysis. The device can be “re-balled” and subjected to full specification testing by either a vendor or 3rd party electrical test laboratory. This approach is preferred though it is both expensive and time consuming. A lower cost approach is to perform continuity testing using a DMM in diode-test or forward-voltage mode, where all signals (or a subset of signals) are tested for continuity with respect to device power and ground. Internal shorts and opens can often be identified using this technique. Once a fault has been verified, the device can be decapsulated and examined internally in a SEM.

Conclusions

A number of BGA failure modes were described and various approaches to conducting failure investigations capable of identifying these failure modes were discussed. In most cases, BGA failure investigations are among the most challenging problems facing OEMs and failure analysts working these devices.

References

[1] R. Sakelson and S. Gold, “Electroless Nickel Immersion Gold And Black Pad", Circuitree [http://www.circuitree.com], 1/01, V14, N1, P10.

[2] B.Houghton, "ITRI project on electroless nickel/immersion gold joint cracking," IPC Printed Circuits Expo '99 proceedings, March 16-19, Long Beach, CA, S18-4.

[3] N. Biunno, "A Root Cause Failure Mechanism for Solder Joint Integrity of Electroless Nickel/Immersion Gold Surface Finishes," Future Circuits International, 1998, pp. 133-137.

[4] Ronald A. Bulwith, Michael Trosky, Louis M. Picchione, Darlene Hug, *The ‘Black Pad’ Failure Mechanism – From Beginning to End*, Global SMT & Packaging Journal’ - September 2002, http://www.alphametals.com/products/solder_solutions/pdf/Global_SMT_and_Pkg_Magazine-The_Black_Pad_Failure_Mechanism.pdf

[5] George Milad & Jim Martin, *Electroless Nickel/Immersion Gold, Solderability and Solder Joint Reliability as Functions of Process Control*, http://www.circuitree.com/CDA/ArticleInformation/features/BNP__Features__Item/0,2133,11666,00.html

[6] Raiyo Aspandiar, *Voids in Solder Joints*, September 21th 2005 SMTA Northwest Chapter Meeting, link.