Afraid of the Dark?

We'll examine the effect of severe black pad defect on solder bonds on BGAs.

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The corrosion of immersion gold-plated, electroless nickel (Ni/P), described as "black pad defect," has been documented in terms of the effect on the surface solderability of printed circuit boards (PCBs) and ball grid arrays (BGAs).[1,2,3] This article describes anomalies associated with the presence of severe black pad on BGA components. Black pad defect can be identified in cross section by an abnormally thick, phosphorus-rich layer, which can deter the formation of nickel/tin (Ni/Sn) intermetallics.

Unique to this analysis is the severity of the black pad as revealed by cracks that extend through the nickel. Corrosion spikes that extend completely through the nickel layer provide a path for the solder to make contact to the copper layer below the electroless nickel. This contact allows the formation of copper/tin (Cu/Sn) intermetallics at the solder ball-to-BGA pad interface. In the BGA assemblies studied, the severity of the black pad is extensive, interfering with the formation of Ni/Sn intermetallics observed in a normal solder bond between Sn63Pb37 solder and a nickel pad. The Cu/Sn intermetallics anchored the BGA to the pad. After mechanical shock, separation occurred between the solder ball and BGA component interface.

In a finished product, black pad is usually only detected when mechanical separation results in a functional failure and is followed by destructive analysis. Prior to mechanical failure, it cannot be identified during visual inspection.

How Does Black Pad Occur?

Black pad defect has been documented in recent years since the push for immersion gold/electroless nickel plating stack-up as a final metal finish. The term *black pad* arises from the visual appearance of a surface affected, which is usually dark gray to black.[1]

Black pad defect has been reported to be the result of galvanic attack to the electroless nickel during the immersion gold plating process.[4,7] The immersion gold plating process involves galvanic displacement. The gold ions in solution accept electrons from the nickel due to the difference in galvanic potential. Gold is thereby deposited onto the surface while the nickel goes into solution.[6] The nickel atoms on the surface are replaced with gold atoms, which is a self limiting process by nickel diffusion.[1]

Different levels of severity of the black pad defect exist, ranging from no effect to solder joint reliability to non-wetting of the electroless nickel surface. The results of this anomaly can be non-wetting of the solder and/or premature failure of the solder joint.[4] Even when the black pad defect is not severe enough to prevent wetting of the solder, as in Ni/Sn intermetallics forming, this defect can still induce failure. Corrosion cracks in the nickel layer, below the Ni/Sn intermetallics, can act as stress risers, causing the intermetallic to fracture.[4]

From the surface, this defect can be viewed as having a mud-cracked appearance. In cross section, black pad may appear as corrosion spikes along the nickel grains or as a black band across the nickel. The depth of corrosion spikes and black band into the nickel will change with severity.[1] The dark region observed by scanning electro microscopy (SEM) is a phosphorus-rich region where the nickel has been depleted.

The Experiment

Boards that experienced mechanical failure of BGA solder attachments to circuit card assemblies (CCAs) were submitted for failure analysis. In each

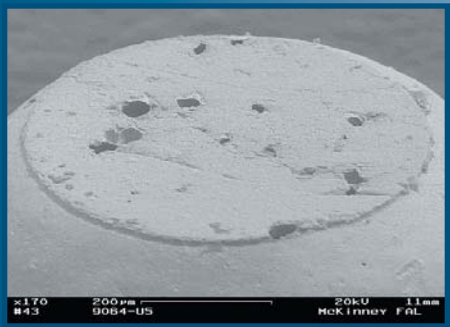

FIGURE 1: SEM image of a ball attachment interface following separation.

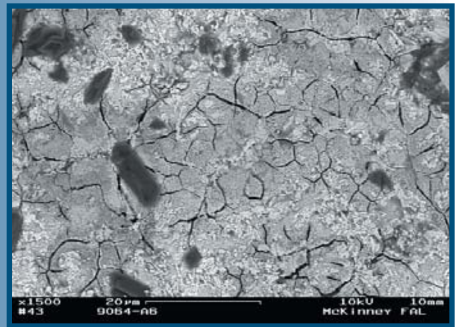

FIGURE 2: Mud-cracked appearance of the surface is characteristic of black pad defect.

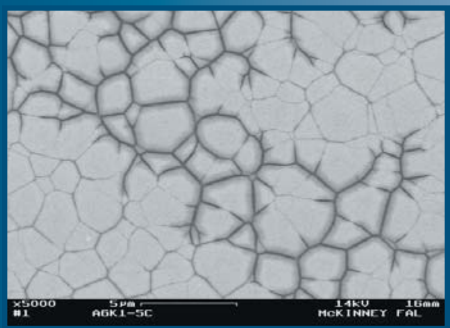

FIGURE 3: Image of a surface with black pad that has been cyanide etched to remove the gold. The black region around the nickel nodules contains a high phosphorus content. The surface has an obvious mud-cracked appearance.

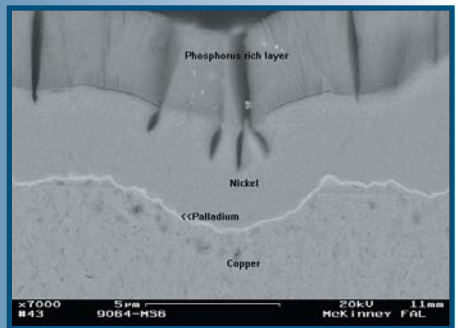

FIGURE 4: Large region of severe black pad with spikes protruding into nickel layer.

case, a BGA had been successfully mounted on a CCA, which initially exhibited no anomalies or defects. The metallurgical stack-up of the BGAs consists of an electroless nickel/immersion gold metal finish on the BGA pads. An underlying copper layer is present below the metal finish. Mechanical shock, in one case the CCA was dropped, resulted in separation between the solder balls and BGA component pads. Analysis of the fractured surfaces revealed evidence of black pad defect.

Analyses of still intact BGA to CCA solder bonds were also investigated on components with similar date codes to the failed BGAs, as well as samples from other suppliers. This investigation was done to verify a widespread reliability problem related to the immersion gold/electroless nickel plating process.

The failed CCAs/BGAs were initially examined optically to view any obvious anomalies. A surface exam was carried out on a field emision-scanning electron microscope (FE-SEM). Elemental data was obtained by energy dispersive spectroscopy (EDS), which was attached to the FE-SEM. Samples, both failures and "good" assemblies, were microsectioned for the solder joints to be further analyzed.

Results and Discussion

• ***Component Failure.*** Mechanical shock resulted in separation of the BGA from the CCA at the ball-to-BGA pad interfaces. The top of the balls and bottom of the BGA component substrate pads were extremely flat, which suggested a brittle failure mechanism at the Sn63Pb37 solder to electroless nickel interfaces (Figure 1). The damage is at the tin/lead (Sn/Pb)-to-nickel interface with no evidence of stress to the remainder of the component body or the circuit card.

Another component of the same part number, supplier and date code was located less than three inches away from the failed component on the same CCA. Optical examination of the still intact component did not reveal any anomalies. However, subsequent destructive analysis revealed defects similar to the failed BGA attachments.

• ***Black Pad Defect.*** SEM analysis of the exposed pad surface on the failed BGA demonstrated *mud cracking*, which is characteristic of severe black pad as shown in the SEM image in Figure 2. The mud-cracked appearance is a result of the corrosion spiking as nickel is depleted from the electroless nickel during the immersion gold plating process. Figure 3 is a backscattered electron FE-SEM image of another pad surface. The BGA did not yet have the solder balls bonded to the pad surface. The gold was removed with a cyanide etch. This surface also has a mud-cracked appearance. The dark region surrounding the nickel nodules is the high phosphorus content due to the corrosion spiking along the nickel grains.

Micro sections of the failed part revealed many areas across the surface of the pads where corrosive spikes were found that extended well into the nickel layer. Figure 4 is a backscattered electron image of the black pad defect in cross section. The dark layer is due to the increased phosphorus content in comparison to the rest of the electroless nickel. The phosphorus-rich zone consumes about half of the electroless nickel layer, which is excessive in comparison to a normal solder joint. In a normal solder joint, the phosphorus-rich layer would be just at the solder to Ni/P plating interface.

Phosphorus levels were determined by EDS standardless quantitative analysis. The phosphorus measured approximately 17.4 weight percent (wt%) in the black pad corrosion area, as compared to a 7.4 wt% in the bulk electroless nickel. This phosphorus level increase, as a result of nickel depletion, is greater than two times the level in the bulk nickel. Some formation of a phosphorus-rich zone is normal when a good solder bond is formed due to the depletion of nickel from the formation of Ni/Sn intermetallics.

Copper/tin intermetallics were also observed during the surface exam. The source of the Cu/Sn intermetallics was investigated

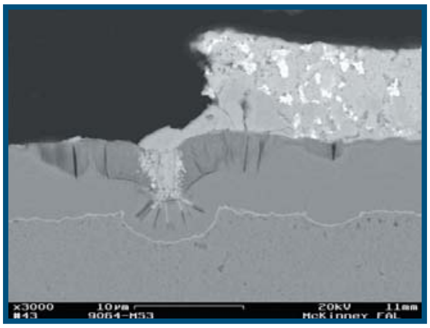

FIGURE 5: Area of severe black pad and corrosion spikes provided a connecting path between the solder and the copper below the nickel layer.

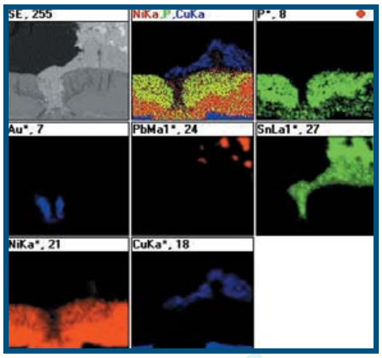

FIGURE 6: EDS elemental dot map showing Cu/Sn intermetallic formation through the black pad corrosion spikes in the nickel layer. The Cu/Sn intermetallics have formed on the pad surface above the nickel layer. Gold is still present on the walls of the large spike through the nickel layer.

since the solder balls were bonded to an electroless nickel pad. Cross-sectional examination determined the Cu/Sn intermetallics at the fracture interfaces were the result of severe black pad and the formation of corrosion crevices completely through the nickel layer. The deep spikes in the nickel created a path between the solder and the underlying copper layer allowing Cu/Sn intermetallics to form at the interface (Figures 5 and 6).

• ***Analysis of Attached Component.*** A component from the same vendor part number and date code that remained attached to the board was microsectioned and examined by SEM. Severe cracking of the solder-to-pad interface was found in six of the 26 solder joints examined in the microsectioned plane. The microcracking was located at the solder to phosphorus-rich black pad interface or through Ni/Sn and Cu/Sn intermetallic regions. The majority of the solder ball-to-pad interfaces contained Cu/Sn intermetallics indicating that severe corrosion spikes from black pad existed in some plane on the majority of the bonded pads.

Summary and Conclusion

Black pad defect-related failures on BGA devices were observed from multiple suppliers whose processes involve electroless nickel/immersion gold metal finish over a copper under plate. The problem typically causes solderability failures such as inhibiting wetting of the solder to the nickel interface by preventing formation of Ni/Sn intermetallics. The black pad problem was not detected until a mechanical failure drew attention to the issue.

Analysis of still intact BGAs revealed multiple solder ball-to-BGA pad interfaces with microcracks. In some solder ball joints, the cracking was substantial and would have resulted in latent failure due to propagation of the cracks and eventual open circuits.

The black pad discussed here was particularly severe with corrosion crevices extending through the nickel layer. This allowed copper migration into the Sn/Pb solder and the formation of Cu/Sn intermetallics. These intermetallics created a brittle zone that can fracture if substantial mechanical shock is applied. The corrosion spikes can act as stress risers assisting in the formation of microcracking in the intermetallic interfaces, thus weakening the joint. In many of the solder ball-to-nickel interfaces examined, the Cu/Sn intermetallics above the nickel provided the primary metallurgical bond between the solder and pad. However, some areas of poor wetting of the solder to the nickel, as a result of the black pad, were also found, as were areas where Ni/Sn intermetallics did form.

To date, a nondestructive technique for identifying susceptible devices prior to assembly is not known. Following assembly, the defective balls exhibit no obvious problem during visual inspection. In fact, the primary concern with these units is that the black pad defect will go undetected until delivery to the customer where a latent mechanical failure may occur. ■

Acknowledgment

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