Board Level Drop Reliability of Epoxy-Containing Sn-58 mass% Bi Solder Joints with Various Surface Finishes

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Board-level drop reliability testing under JEDEC (Joint Electron Device Engineering Council) drop conditions was conducted for low-temperature Sn-58mass%Bi solder joints. The effects of surface finish and the number of reflow processes (one, three, or five) on the drop reliability of the Sn-58Bi joints were evaluated. Three types of surface finishes were used including electroless nickel immersion gold (ENIG), electroless nickel electroless palladium immersion gold (ENEPIG), and organic solderability preservatives (OSP). We successfully fabricated six types of drop test specimens with various surface finishes and bonding materials, and then performed the board-level drop tests. The board-level drop reliability was improved when using the composite Sn-58Bi solder with epoxy as compared to Sn-58Bi solder without epoxy. In addition, the reliability of the Sn-58Bi epoxy solder/OSP joint was better than both the ENIG and ENEPIG surface finishes. When the number of reflow processes increased, the drop reliability showed two different behaviors; specifically, the reliability of the ENIG and ENEPIG surface finishes decreased while the OSP surface finish improved. The existence of epoxy in the solder paste improved the drop reliability of the solder joints. After drop testing, cracks propagated differently with different surface finishes, namely between Ni₃Sn₄ IMCs and the Ni-P layer for the ENIG surface finish, between Ni₃Sn₄ IMCs and the solder bulk for the ENEPIG surface finish, and within the solder bulk for the OSP surface finish. These data show that, when it is necessary to perform repeated reflow processes for electronic components, solder joints with an OSP surface finish provide better drop test reliability results. [doi:10.2320/matertrans.M2015260]

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1. Introduction

The board level reliability of solder joints during drop impact is of great concern in electronic packaging.¹⁾ Accidentally dropping portable electronic devices such as mobile phones, personal digital assistants, digital cameras, and tablet personal computers results in impacts that may cause damage or device failure. The mechanical stresses associated with such an impact are therefore the most severe conditions considered in determining the board-level reliability of portable electronics devices. Due to the need for an industrial standard for drop impacts, many researchers have proposed various drop test methodologies.^{2–4)} JESD22-B111, which describes board-level drop testing of handheld electronic products, was declared the standard test by the Joint Electron Device Engineering Council (JEDEC).⁵⁾

Many researchers have studied the mechanical properties of printed circuit boards (PCBs) that include a ball grid array (BGA) using the JEDEC standard impact methodology.^{6–9)} A BGA is a form of surface mount technology consisting of an array of solder joints. BGA connectors can be stressed to failure, resulting in the failure of the PCB; this stress can occur during device assembly, testing, shipment, or under certain environmental conditions. In order to enhance the reliability of BGA connectors under mechanical stress, epoxy underfills have been developed.^{10–12)}

The electronic industry relies on Pb-free solders because of the harmful effects of lead on the environment and human health. One of the important requirements for electronics

solders is a processing temperature equal to or lower than conventional Sn-Pb solder. Therefore, a representative low-temperature Pb-free solder, Sn-58 mass%Bi solder, is nominated as a substitutable solder alloy. The low melting point of Sn-Bi solder makes it suitable for soldering temperature-sensitive components and substrates. While Pb-free solders generally show lower drop-impact resistance than conventional Pb-based solder,^{13–15)} some Pb-free solders (Sn-3Ag-0.5Cu, Sn-9Zn, and Sn-8Zn-3Bi) show better impact toughness than Pb-based solders such as Sn-Pb.¹⁵⁾

Data and reports on comparative drop reliability studies between general solder joints and epoxy-containing solder joints are still lacking, especially when combined with low-melting-temperature Sn-58Bi solder. In this study, we investigated the mechanical drop properties of a low-melting temperature Sn-58Bi epoxy solder by conducting board level drop tests according to JEDEC standard JESD22-B111. The mechanical drop properties were measured and compared with various surface finishes on Cu substrates including electroless nickel immersion gold (ENIG), electroless nickel electroless palladium immersion gold (ENEPIG), and organic solderability preservative (OSP). The results are compared to those obtained for the Sn-58Bi solder joint without epoxy.

2. Experimental Procedures

Figure 1 shows schematic illustrations of the bottom and top PCBs used in this study. Both top and bottom PCBs consist of a solder mask defined (SMD)-type flame retardant-4 (FR-4) laminate with 100 (10 × 10 arrays) I/O points. This structure allowed us to construct a daisy chain circuit

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between the bottom and top PCBs. The size of the opening in the bonding pad was $200\text{ }\mu\text{m}$, and the pitch was $800\text{ }\mu\text{m}$. The geometries of the top and bottom PCBs conformed to the JEDEC standard JESD22-B111. Three types of surface finishes, ENIG ($7\text{ }\mu\text{m}$ Ni-P/ $0.1\text{ }\mu\text{m}$ Au), ENEPIG ($7\text{ }\mu\text{m}$ Ni-P/ $0.1\text{ }\mu\text{m}$ Pd/ $0.1\text{ }\mu\text{m}$ Au), and OSP, were prepared for board-level drop testing. The pad of the OSP PCB was constructed by plating an OSP layer onto the underlying Cu pad. The thickness of the OSP layer was approximately $0.3\text{ }\mu\text{m}$.

Two kinds of solder joints were prepared to evaluate the effect of epoxy in the solder material on the board-level drop test performance: eutectic Sn-58Bi (58 mass% Bi, Alpha metal) and eutectic Sn-58Bi with epoxy (Alpha metal). Both Sn-58Bi solder pastes were screen printed on the bottom of the PCBs to form solder bumps. The bumps on the top PCBs were aligned with the bumps on the substrate PCBs. Reflow was then carried out in an IR four-zone reflow machine (RF-430-Ne, Japan Pulse Laboratory Co. Ltd). The peak reflow temperature was 200°C . To evaluate the effect of multiple

reflow processes on the board-level drop reliability of the solder joints, a single reflow process was carried out and followed by three and five cycle reflow process tests.

Board-level drop testing was conducted after soldering via the reflow process according to JEDEC standard JESD22-111B. The drop test board was fixed to the drop table on the drop tester (SD-10, LAB, USA) at the four corners with the mounted packages facing downward. The drop table was released at a certain height and dropped freely to repeatedly impact the strike surface. Our drop test conditions corresponded to JEDEC drop test condition A. The test was regarded as a failure when the resistance increased by more than $100\text{ }\Omega$ from the initial resistance. When such an increase in resistance is observed in at least 3 out of 5 shock tests, the sample was regarded as a failure. The interfacial microstructure and intermetallic compound (IMC) morphology were observed using a scanning electron microscope (SEM, Hitachi S-3000H) and the composition of the IMC was measured using energy dispersive X-ray spectroscopy (EDX). After the drop tests, the fracture surfaces were observed via SEM and EDX.

3. Results and Discussion

Board-level drop test specimens were formed after reflowing at 200°C for 60 s. We successfully fabricated six types of drop test specimens with various surface finishes and bonding materials, and then performed the board-level drop tests. Figure 2 shows Weibull plots of failures for board-level drop tests conducted to determine the effect of surface finish for various bonding materials (with and without epoxy). The failure behavior of the Sn-58Bi solder joint without epoxy (Fig. 2(a)) was similar regardless of surface finish. On the other hand, the OSP surface finish performed the best for the Sn-58Bi solder joint with epoxy, while similar results were obtained for the ENEPIG and ENIG surface finishes (Fig. 2(b)). Therefore, the reliability of the Sn-58Bi solder (w/epoxy)/OSP joint was better than both the ENIG and ENEPIG surface finishes. These results for various surface finishes are consistent with those of other solder joints (SAC solder joints).^{16–19)}

The presence of epoxy in the Sn-58Bi solder slightly improved the drop reliability for ENIG and ENEPIG surface

Fig. 1 Schematic diagrams of component (top) and substrate (bottom) PCBs for board-level drop testing.

Fig. 2 Weibull plots of failure under board-level drop testing to determine the effect of surface finish for various bonding materials: (a) Sn-58Bi solder joint without epoxy after one reflow and (b) Sn-58Bi epoxy solder after one reflow.

Fig. 3 Weibull plots of failure events for (a) three and (b) five reflows in Sn-58Bi solder (w/epoxy) joints for various surface finishes under board-level drop testing.

Fig. 4 Cross-sectional SEM images of the failed Sn-58Bi epoxy solder/ENIG joint under board-level drop testing after 5 reflows.

Fig. 5 Cross-sectional SEM images of the failed Sn-58Bi epoxy solder/ENEPIG joint under board-level drop testing after 5 reflows.

finishes compared to the Sn-58Bi solder joints without epoxy (black circles and red squares in Fig. 2). In contrast, the presence of epoxy significantly improved the drop reliability for the OSP surface finish (green diamonds in Fig. 2). Therefore, the presence of the epoxy in solder joints enhanced the drop test reliability of the solder joints regardless of surface finish.

Figure 3 shows the Weibull plots of drop-test failure events for three and five reflows in the Sn-58Bi epoxy solder joints for various surface finishes. The results of the Sn-58Bi epoxy solder joint for one reflow process are provided in Fig. 2(b). The failure event behaviors of the Sn-58Bi epoxy solder/ENIG joints were similar to the results for ENEPIG joints after three reflow processes, while the failure event behavior of the Sn-58Bi epoxy solder/OSP joints was superior to those with ENIG and ENEPIG surface finishes. Similar results were obtained after five reflow processes. Overall, the drop reliability of the ENEPIG joints was better than that of the ENIG joints. The Sn-58Bi epoxy solder/OSP joints showed superior reliability even as the number of reflow processes increased. In contrast, the drop reliability of the Sn-58Bi epoxy solder joints with ENIG and ENEPIG surface finishes decreased as the number of reflow processes increased.

Figure 4 shows cross-sectional SEM images of the failed Sn-58Bi epoxy solder/ENIG joint after five reflow processes. In the solder joint, a Ni_3Sn_4 IMC was formed by the reaction between the Ni-P layer and the solder. During initial

reflowing, the entire Au layer on the Ni layer dissolved into the molten solder, and the Sn-58Bi solder formed a uniform and continuous Ni_3Sn_4 IMC (chunk-shaped) at the solder/Ni interface.^{20,21)} In a previous work, we investigated the interfacial reactions and joint mechanical reliability of Sn-58Bi solder with three surface finishes, OSP, ENIG, and ENEPIG.²²⁾ In the study, we successfully identified the interfacial products during the reflow reaction. In the current study, epoxy fillets formed between the solder bulk and the top PCB, or between the solder bulk and the bottom PCB. Fracturing occurred between IMCs and the Ni-P layer of the bottom PCB. Generally, fractures occurred on the board side after drop testing due to a large deformation of the bottom substrate.⁹⁾ A few epoxy fillets were released and removed during board-level drop testing. These epoxy fillets are indicated with white dotted lines in Fig. 4.

Figure 5 shows the cross-sectional SEM images of the failed Sn-58Bi epoxy solder/ENEPIG joint under board-level drop testing after five reflows. During the initial reflow reaction, the Au and Pd layers of the ENEPIG layer dissolved into the molten solder, and the Sn-58Bi solder reacted with the Ni layer, resulting in the formation of a Ni_3Sn_4 IMC. Chunk-shaped Ni_3Sn_4 IMCs were prevalent at the interface. Epoxy fillets formed at four corners between the solder bump and top/bottom PCBs. Fracturing occurred directly over the interfaces between the solder bulk and IMCs.

Figure 6 shows cross-sectional SEM images of the failed Sn-58Bi epoxy solder/OSP joint under board-level drop

Fig. 6 Cross-sectional SEM images of the failed Sn-58Bi epoxy/OSP joint under board-level drop testing after 5 reflows.

testing after five reflow processes. In the solder joint, scallop-type Cu_6Sn_5 IMCs formed at both interfaces between the Cu and solder. Fracturing occurred within the bulk solder near the bottom substrate interface.

Figures 7, 8, and 9 show the fracture surfaces of the Sn-58Bi epoxy solder joints with ENIG, ENEPIG, and OSP surface finishes, respectively. In the case of the Sn-58Bi epoxy solder/ENIG joint (Fig. 7), fractures occurred along the interface between the Ni_3Sn_4 IMCs and the Ni-P layer after five reflow processes. Fractures also occurred after one reflow at the Ni_3Sn_4 IMC/Ni-P interface in the Sn-58Bi solder joint without epoxy; indicating that the fracture site did not change regardless of the presence of epoxy within the solder materials. In the case of the Sn-58Bi epoxy solder/

ENIG	Sn-58Bi epoxy solder (5 reflow)		Sn-58Bi (1 reflow)	
	Bottom PCB	Top PCB	Bottom PCB	Top PCB
x400				
x10,000				

Fig. 7 Fracture surfaces of the Sn-58Bi/ENIG solder joints after drop tests.

ENEPIG	Sn-58Bi epoxy solder (5 reflow)		Sn-58Bi (1 reflow)	
	Bottom PCB	Top PCB	Bottom PCB	Top PCB
x400				
x10,000				

Fig. 8 Fracture surfaces of the Sn-58Bi/ENEPIG solder joints after drop tests.

Fig. 9 Fracture surfaces of the Sn-58Bi/OSP solder joints after drop tests.

ENEPIG joint (Fig. 8), fractures occurred partially at the interface between the Ni_3Sn_4 IMCs and partially in the solder bulk after five reflows. In the case of the Sn-58Bi solder/OSP joint, fractures occurred within the bulk solder near the bottom PCB interface, as shown in Fig. 9. The fracture analysis results of Figs. 7, 8, and 9 are in agreement with the cross-sectional microstructures of the failed Sn-58Bi solder joints with ENIG, ENEPIG, and OSP surface finishes, respectively. Therefore, repeated mechanical stresses under the board-level drop test were concentrated somewhere in the Sn-58Bi epoxy solder joint, and cracks were created at the weakest points. Cracks propagated differently with different surface finishes, namely between Ni_3Sn_4 IMCs and the Ni-P layer for the ENIG surface finish, between Ni_3Sn_4 IMCs and the solder bulk for the ENEPIG surface finish, and within the solder bulk for the OSP surface finish.

During the solder reflow process, bump formation and epoxy curing occurred simultaneously. Epoxy curing results in the formation of epoxy fillets around the solder bump between the solder bulk and the PCBs (both the top and bottom PCB), enhancing the strength of the solder joint as the fillets hold the solder bulk and PCBs together. During the reflow process, IMCs such as Ni_3Sn_4 and Cu_6Sn_5 are formed depending on the surface finish. The structure of the OSP surface finish was different from that of the ENIG and ENEPIG surface finishes. ENIG and ENEPIG consisted of an electroless plating layer (ENEPIG had a Pd and Ni layer, ENIG has a Ni layer) and an immersion Au layer. In contrast, the OSP surface finish consisted of an organic compound on a Cu surface. The solder reaction between the Ni layer of ENIG and the Sn of the Sn-58Bi solder formed Ni_3Sn_4 IMCs during the reflow process. Similarly, the solder reaction between the Pd/Ni layer of the ENEPIG surface finish and Sn of the Sn-58Bi solder formed Ni_3Sn_4 IMCs during the reflow process. On the other hand, the solder reaction between the Cu pad of the OSP surface finish and the Sn of the Sn-58Bi solder primarily formed Cu_6Sn_5 IMCs. As the reflow process

was repeated, the reliability of the Sn-58Bi epoxy solder joints for ENIG and ENEPIG surface finishes decreased while that of the OSP surface finish improved. The strength of the Sn-58Bi epoxy solder joints was enhanced by the formation of fillets as compared to the solder joints without epoxy. The drop reliability depended strongly on the interfacial IMCs and surface finish materials. The drop lifetime of the ENIG joints was shorter than that of the ENEPIG joint due to the brittle IMC/Ni-P interface in the ENIG joints.⁹⁾ We found that the drop reliability of the OSP joints was superior to that of both ENIG and ENEPIG surface finishes. A similar result was reported in a previous study.²³⁾ This may be due to the relatively strong adhesion between the solder/ Cu_6Sn_5 IMC/Cu substrate and also to the absence of a brittle Ni-P layer in the OSP joint. Schematic diagrams summarizing our understanding of failure in these materials are provided in Fig. 10.

4. Conclusions

We investigated reliability under board-level drop testing according to JEDEC standard JESD22-111 for PCBs with Sn-58Bi solder (both with and without epoxy) joints exposed to up to five reflow processes. We found unique mechanical reliability and fracture behavior in the Sn-58Bi solder joints for various surface finishes (ENIG, ENEPIG and OSP). The mechanical reliability of the joint with the ENIG surface finish decreased with an increasing number of reflow processes. The ENIG joints fractured along the interface between the Ni_3Sn_4 IMCs and the Ni-P layer at the bottom PCB. The mechanical reliability of the ENEPIG surface finish also decreased with increasing reflow processes, and a partial fracture occurred between the Ni_3Sn_4 IMCs and solder bulk on the bottom PCB. The mechanical reliability improved as reflow was repeated for the OSP surface finish, and fractures occurred within the solder bulk on the bottom PCB. The fracture depended on the IMC and surface finish

Fig. 10 Schematic diagrams of fracture sites after board-level drop testing.

material, and each sample showed a distinctive fracture mode. The drop reliability of the OSP joints was superior to those of ENIG and ENEPIG surface finishes due to relatively strong adhesion between the solder/ Cu_6Sn_5 IMC/Cu substrate and the absence of a brittle Ni-P layer in the OSP joint.

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