BGA Jointing Property of Sn–8.8 mass% Zn and Sn–8.0 mass% Zn–3.0 mass% Bi Solder on Electroless Nickel–Phosphorus/Immersion Gold Plated Substrates*

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The BGA jointing properties including the joint strength and the interfacial structure have been investigated in detail between the lead-free solders containing Sn–8.8Zn and Sn–8.0Zn–3.0Bi with low melting temperature and the immersion gold plated film on the electroless nickel–phosphorus deposits. The results indicate that both Sn–8.8Zn and Sn–8.0Zn–3.0Bi solder can be readily jointed with the substrate in the same way as the conventional Sn–37Pb solder at the peak temperature of 230°C. The joint strength of Sn–8.8Zn solder is higher than that of Sn–8.0Zn–3.0Bi solder, and both of them are higher than that of Sn–37Pb under same surface finishing. Moreover, γ2(AuZn3) intermetallic compound occurs as the reaction layer at Sn–8.8Zn and Sn–8.0Zn–3.0Bi joints, and the bismuth crystals occur at Sn–8.0Zn–3.0Bi joint. The hot bump pull testing results clearly show that the fracture of solder ball occurs along the reaction layer or bismuth crystals in the joint causes the decrease of joint strength.

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1. Introduction

Recently the application of ball grid array (BGA) packages for electronic devices has mainly become more common for portable equipment, because BGA has the advantage of being suitable for high-density mounting. Solder ball of conventional Sn–Pb alloy has been used to connect BGA package on printed circuit board (PCB).1) Electroless nickel-phosphorus (Ni–P) and immersion gold (Au) plating process has been used to improve corrosion endurance and wettability of solder as surface finishing for PCB of solder ball mounting. Copper circuit of PCB is coated by Ni–P deposit, and then immersion Au film finishes the Ni–P/Cu as topcoat. Suitable plating chemicals have been developed for this solder mounting.2) The reliability of solder joint is important to connect package on PCB. Analysis of the jointing structure will be expected to be available to improve the reliability.

In the meantime, lead (Pb)-free solder has been desired as replacement for the conventional Sn–Pb solder because Pb induces environmental pollution. Some kinds of Pb-free solder have already designed for solder mounting.3,4) One of them is Sn–Ag–Cu solder. Sn–Ag–Cu solder has been expected to apply as highly reliable Pb-free solder, because of better thermal and mechanical properties than other Pb-free solders.5–7) But the temperature of heat treatment to joint Sn–Ag–Cu solder is higher than that of conventional Sn–Pb solder to damage some kinds of electric devices. Thus the Sn–Ag–Cu solder can not apply for all kinds of electric devices. So Sn–Zn system solder alloy. Bi contained within Sn–8.0Zn–3.0Bi is third element to lower the melting temperature. And Sn–Zn system solder alloy. Bi contained within Sn–8.8Zn–3.0Bi solder拉is clearly show that the fracture of solder ball occurs along the reaction layer or bismuth crystals in the joint causes the decrease of joint strength.

Sn–Zn system solder alloy. Bi contained within Sn–8.0Zn–3.0Bi solder拉is third element to lower the melting temperature. And we have investigated the jointing properties of both solders on Au/Ni–P deposit.

2. Experimental

2.1 Making samples

As shown in Fig. 1, copper deposit (Cu thickness: 18µm), which was plated on copper foil (Cu thickness: 35 µm) bonded on glass-epoxy resin (FR-4), covered having ball pad mouth (φ = 0.5 mm) with solder resist was prepared as substrate for this study. Three kinds of electroless Ni–P deposit, which have different phosphorus content (Ni–4–6 mass%P, Ni–6–8 mass%P and Ni–9–10 mass%P), were plated on the copper ball pad, and then immersion Au film finished the Ni–P deposits as top coat. At that time, each target thickness of Ni–P deposit and Au film was 5.0 µm and 0.05 µm respectively to be the same thickness as industrial electroless Ni–P and immersion Au plating process standard. Moreover, thicker immersion Au film of 0.1 µm was also prepared as comparison on the other substrates.9) Plating time of Au film of 0.05 µm and 0.1 µm on Ni–P deposit was for 7 min and 20 min respectively.

The thickness of each sample was confirmed by fluorescence X-ray spectrometer (Seiko instrument: SEA5120). Thinner Au thickness on two different kinds of lower

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Fig. 1 Test broad of solder mask defined land pad type.
phosphorus deposits (Ni–4–6 mass%P and Ni–6–8 mass%P) was 0.05 μm to be target thickness with 7 min plating. But each thickness of thicker Au samples on both lower phosphorus deposits with 20 min plating, which was thicker than 0.1 μm as target thickness, was 0.12 μm and 0.13 μm respectively. On the other hand, both of Au thickness on Ni–9–10 mass%P with 7 min and 20 min plating, which were thinner than these target thickness, were 0.04 μm and 0.08 μm respectively. Since phosphorus content of Ni–9–10 mass%P is relatively higher than that of Ni–4–6 mass%P and Ni–6–8 mass%P, it is thought that the displacement of Au onto Ni–9–10 mass%P deposit is inhibited.

Sn–8.8Zn or Sn–8.0Zn–3.0Bi solder balls were mounted on plated copper ball pads coated with flux. These were baked through desktop reflow furnace (Japan pulse laboratories: RF-330) to join solder balls on the pads under the condition as follows. Conveyer speed is 340 mm/min and the pre-heat temperature is 160 °C prior to peak temperature of 230°C. Although solder ball diameter (φ = 0.45 mm) is smaller than that of ball pad, solder balls were melted by heat treatment and wet completely on whole area of the pad as shown in Fig. 1.

### 2.2 Pull strength of solder ball

The strength of solder joint was measured following hot bump pull method. The pulling rate was constant with 2.2 Pull strength of solder ball shown in Fig. 1. These were baked through desktop reflow furnace (Japan pulse laboratories: RF-330) to join solder balls on the pads under the condition as follows. Conveyer speed is 340 mm/min and the pre-heat temperature is 160 °C prior to peak temperature of 230°C. Although solder ball diameter (φ = 0.45 mm) is smaller than that of ball pad, solder balls were melted by heat treatment and wet completely on whole area of the pad as shown in Fig. 1.

### 2.3 Analysis of structure

Grinding the solder balls jointing substrates on abrasive made the cross-section samples. Surrounding of reaction interface within the cross-section samples were observed to analyze structure and composition of the joint interface by scanning electron microscope (SEM; JEOL: JSM-5600LV) and electron probe micro analyzer (EPMA; JEOL: JXA-8900). Destructed surface after hot bump pull test was also analyzed by EPMA.

Moreover, transmission electron microscope (TEM; JEOL: JEM-2000FE) observation was conducted to analyze the structure at the reaction interface in more detail. Electron diffraction patterns were also got to analyze the crystal structure at the reaction interface simultaneously. At that time, the method to make TEM specimen was as follows. Solder ball jointing substrate which is cut in the cross-section direction is grounded on abrasive paper to be approximately 30 μm thickness, and then it is finished to be foil as TEM specimen using focused ion beam system (FIB; Micrion: JFIB2100).

### 3. Results and Discussion

#### 3.1 Joint strength

Figure 2 shows the strengths of (A) Sn–8.8Zn and (B) Sn–8.0Zn–3.0Bi jointed on six kinds of Au/Ni–P deposit. Comparison (A) and (B) in Fig. 2 exhibited that the average strengths of (A) Sn–8.8Zn on six kinds of Au/Ni–P deposit was 3 to 5 N higher than that of (B) Sn–8.0Zn–3.0Bi. Although authors have already reported that the joint strength of Sn–37Pb jointed on Au/Ni–P deposit decreased with increasing phosphorus content contained within Ni–P deposit, the results of joint strengths for Sn–8.8Zn and Sn–8.0Zn–3.0Bi joint don’t indicate the affect of phosphorus content on joint strength. Comparing the strengths of different Au thickness on three kinds of Ni–P deposit for both solder alloys to estimate effect of Au thickness on the joint strength, each strength of thicker Au thickness of 0.12 μm and 0.13 μm on Ni–4–6 mass%P and Ni–6–8 mass%P deposit was relatively lower than those of thinner Au thickness of 0.05 μm. However, each strength of both Au thickness on Ni–9–10 mass%P deposit was almost same. As mentioned in section 2.1, Au thickness on Ni–9–10 mass%P deposit is thinner than those on Ni–4–6 mass%P and Ni–6–8 mass%P deposit, and the difference of both Au thickness on Ni–9–10 mass%P with 7 min and 20 min plating deposit is smaller than those on Ni–4–6 mass%P and Ni–6–8 mass%P. Thus, the strength for Ni–9–10 mass%P might be hardly effected by the difference of Au thickness.

We have also reported that each average strength of Sn–37Pb, Sn–3.5Ag and Sn–3.5Ag–0.75Cu solder jointed on Au (0.05 μm)/Ni–6–8 mass%P (5.0 μm) were 11 N, 11 N and 15 N respectively. Comparing with both strengths of Sn–8.8Zn and Sn–8.0Zn–3.0Bi jointed on Au (0.05 μm)/Ni–6–8 mass%P (5.0 μm) shown in Fig. 2, it is found that the strength of Sn–8.8Zn is higher than that of Sn–37Pb, Sn–3.5Ag and Sn–3.5Ag–0.75Cu joint, and the strength of Sn–8.0Zn–3.0Bi was equivalent to that of Sn–3.5Ag–0.75Cu.
joint and higher than that of Sn–37Pb and Sn–3.5Ag joint.

For Sn–37Pb and Sn–3.5Ag joint, Ni–Sn intermetallic compound (Ni₃Sn₄) is formed along the joint interface, simultaneously phosphorus enriched layer along the joint interface is formed by diffusion of Ni contained within Ni–P deposit into solder side. The regional phosphorus concentration along the reaction interface deteriorates the strength of solder joint. Ascent of phosphorus content within Ni–P deposit accelerates deterioration of joint strength. However, the strengths of Sn–8.8Zn and Sn–8.0Zn–3.0Bi joint are not affected by phosphorus content within Ni–P deposit (Fig. 2). Thus, it supposes that the jointing structures of Sn–8.8Zn and Sn–Ag system solder alloy are rather different from that of Sn–37Pb and Sn–Ag system solder alloy.

3.2 Analysis of jointing structure

Figure 3 shows composition images using SEM at the area of joint interface of (A) Sn–8.8Zn and (B) Sn–8.0Zn–3.0Bi. Reaction layer was recognized along the joint interface, the reaction layer exhibited thickening tendency with increasing plating time of immersion Au. The reaction layer was analyzed using mapping method of EPMA. The mapping images for Sn–8.8Zn and Sn–8.0Zn–3.0Bi joint are shown at (a) to (f) in Fig. 4 and Fig. 5 respectively, where each (a) to (f) are same area. Judging from strongly detect of Au and Zn at reaction layer in Fig. 4 and Fig. 5, it is considered that Au–Zn intermetallic compound was formed along the joint interface.

Furthermore, TEM observation was conducted at the area of joint interface in cross-section to analyze the reaction layer of Sn–8.8Zn and Sn–8.0Zn–3.0Bi joint in more detail. The results of them are shown in Figs. 6 and 7 respectively. (a) Bright-field image in Fig. 6 is synthesized with two contiguous pictures at the same joint interface. Electron diffraction patterns of (b-1), (b-2) and (b-3) were got at the circular point in (a) Bright-field image. Table 1 indicates analysis results of each diffraction pattern in Fig. 6. From the analysis, it is identified that the territory of (b-1) was Cu, the layer of (b-2) was Ni–P deposit, and γ₂(AuZn₃) intermetallic compound existed at the point of (b-3). Thus, γ₂(AuZn₃) intermetallic compound is formed as the reaction layer along the joint interface of Sn–8.8Zn joint. On the other hand for Sn–8.0Zn–3.0Bi joint, it is identified from the analysis of each diffraction pattern in Fig. 7 that the layer mixed with Ni3P and Ni was formed at the point of (b-1), γ₂(AuZn₃) intermetallic compound and Bi crystal existed at the point of (b-2), and the area of (b-3) was solder alloy composed of β-Sn, Zn and Bi (Table 2). Thus, it is found that γ₂(AuZn₃) and Bi crystal form within the reaction layer. As mentioned above, Au film on Ni–P deposit diffuses into each solder alloy for Sn–37 mass%Pb and Sn–3.5Ag joint and then Ni–Sn intermetallic compound (Ni₃Sn₄) layer is formed by reacting Ni contained within Ni–P deposit with Sn within each solder alloy and phosphorus enriched layer is formed along the reaction interface at the same time. However for this work, it

![Image](image-url)
Fig. 4 Mapping analysis images of the Sn–8.8Zn joint interface.

Fig. 5 Mapping analysis images of the Sn–8.0Zn–3.0Bi joint interface.

Fig. 6 TEM image of Sn–8.8Zn joint interface on Au/Ni–P. (a) Bright-field image. (b) Electron diffraction patterns.
is found that the $\gamma_2(AuZn_3)$ layer or the layer mixed with $\gamma_2(AuZn_3)$ and Bi crystal is formed for Sn–8.8Zn and Sn–8.0Zn–3.0Bi joint respectively.

Next to jointing structure, we discuss where joint interface was destructed by hot bump pull test. Figures 8 and 9 show mapping analysis images for each element on the ball pad side and solder ball backside after hot bump pull test for Sn–8.8Zn and Sn–8.0Zn–3.0Bi joint respectively. (a) Ball pad side images in Figs. 8 and 9 indicate that Ni and P are detected but Sn is not detected. Whereas (b) solder ball backside images in Figs. 8 and 9 indicate that Ni and P are hardly detected but Sn is strongly detected. Au and Zn are detected on both sides in Figs. 8 and 9 and the intensity of detection on solder ball backside is slightly stronger than that on ball pad side. Also Bi images as shown in Fig. 9 indicate relatively strong detection on solder ball backside and slightly detection on ball pad side. Since Ni and P are detected on ball pad side and Au and Zn are detected on both sides in Figs. 8 and 9, it is considered that Sn–8.8Zn and Sn–8.0Zn–3.0Bi joint is destructed within the $\gamma_2(AuZn_3)$ layer and the mixed layer of $\gamma_2(AuZn_3)$ and Bi crystal as reaction layer respectively. Thus it supposes that the $\gamma_2(AuZn_3)$ layer...
or the mixed layer of $\gamma_2(AuZn_3)$ and Bi crystal is the most fragile layer for each joint.

As mentioned in section 3.1, joint strengths are not affected by phosphorus content within Ni–P deposit for Sn–8.8Zn and Sn–8.0Zn–3.0Bi joint. It may relate with the different jointing way as follows. Sn–8.8Zn and Sn–8.0Zn–3.0Bi solder alloy are able to joint by the reaction of Zn within each solder alloy with Au film on Ni–P deposit. Whereas conventional Sn–37 mass%Pb and Sn–Ag system solder alloy are able to joint by the reaction of Sn within each solder alloy with Ni within Ni–P deposit. Also, the joint strengths of Sn–8.8Zn and Sn–8.0Zn–3.0Bi joint slightly decrease with prolonging of plating time of immersion Au (thickening of Au thickness) as shown in (A) and (B) of Fig. 2. It may be affected by thickening of the reaction layer formed with $\gamma_2(AuZn_3)$ or $\gamma_2(AuZn_3)$ and Bi crystal (Fig. 3). Moreover, joint strength of (B) Sn–8.0Zn–3.0Bi is inferior to that of (A) Sn–8.8Zn as shown in Fig. 2. The decrease of joint strength for Sn–8.0Zn–3.0Bi joint may be concerned with existence of Bi crystal into the reaction layer.

4. Conclusion

The measurement of joint strength of BGA solder joint and the analysis of the jointing structure at the area of interface were conducted for the systems of Sn–8.8Zn and Sn–8.0Zn–3.0Bi jointed on Au/Ni–P deposit. As the results of them, it was clear as follows.

1. The joint strengths of Sn–8.8Zn and Sn–8.0Zn–3.0Bi jointed on Au/Ni–P deposit are superior to that of Sn–37Pb joint.
2. The joint strength of Sn–8.0Zn–3.0Bi added with Bi to lower melting point is inferior to that of Sn–8.8Zn.
3. The $\gamma_2(AuZn_3)$ intermetallic compound layer and the mixed layer of $\gamma_2(AuZn_3)$ intermetallic compound and Bi crystal are formed as reaction layer for Sn–8.8Zn and Sn–8.0Zn–3.0Bi joint respectively.
4. The joints of Sn–8.8Zn and Sn–8.0Zn–3.0Bi solder are destructed within the reaction layer, and thickening of the reaction layer or Bi crystal in the joint causes the decrease of joint strength.

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(a) Ball pad side  (b) Solder ball back side

Fig. 9 Mapping analysis images of the destructed surface of Sn–8.0Zn–3.0Bi joint.