Influence of the Interfacial Reaction Layer on Reliability of CSP Joints Using Sn-8Zn-3Bi Solder and Ni/Au Plating

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In order to investigate the use of Sn-8Zn-3Bi solder as a potential substitute for Sn-Pb solder, which has a lower melting point than Sn-Ag family solders for CSP assembly, we studied mechanical properties of CSP joints plated with varying thicknesses of Au and Ni on Cu pad. Joint strength and other mechanical properties were evaluated in relation to reflow peak temperature. The combination of 0.05 μm Au plating thickness and reflow peak temperature of 498 K resulted in the best joint reliability in the as reflowed condition and also after aging treatment. The joint was founded to have thin Ni_3Sn_4 type interfacial reaction layer that included Cu and Zn between the solder and the Ni plating. This interfacial structure was shown to improve the joint strength.

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1. Introduction

Sn-Pb eutectic solder has been widely used in the electronics industry for electrically connecting packages on print circuit boards (PCBs). However, solder has been increasingly restricted because it contains lead, which is harmful to humans body. The development of alternative lead-free solder has been the focus of increasing research interest.^{1,2)} Among the alternative solders, several alloy materials have been developed, and among these, the Sn-Ag and Sn-Zn family solder are considered to be the best alternatives. Although Sn-Ag family solders, such as Sn-Ag-Cu solders, have good mechanical and thermal properties, their melting point are higher than the Sn-Pb eutectic solder by about 40 K. As a result, problems are often encountered with regard to heat resistance of electronic components.¹⁾ In contrast, Sn-Zn family solders have good mechanical property and equivalent melting temperature as the Sn-Pb eutectic solder.¹⁾ However, Sn-Zn family solders have poor wettability on Cu and their joint properties are known to deteriorate after thermal exposure due to interfacial reactions. To prevent diffusion of Cu from a PCB pad into solder and to improve wettability, Ni and Au must be needed to plated on the Cu pad. However the interfacial reaction between the Ni/Au plating on Cu and Sn-Zn solders and its effects on joint properties are not clear. In addition, Chip Size package (CSP) and Ball Grid Array (BGA) package have been used to achieve higher density assembly than can be achieved with more conventional packages such as Quad Flat Package (QFP). This has occurred in response to continuing minimization and weight reduction requirement.²⁾ Sn-Zn family solders are desirable for CSP and BGA applications because of their low melting points avoiding thermal damage of the components. In this study, CSP was reflow-soldered onto a PCB pad using a Sn-8Zn-3Bi solder. Various thicknesses of Au plating on Cu pad and a range of reflow peak temperatures

were investigated. The effect of these conditions were studied with respect to interfacial reactions and joint reliability.

2. Experimental Procedure

In this study, we used a solder paste of Sn-8Zn-3Bi. The structure and specification of the CSP used in this study are shown in Fig. 1. The composition of the solder ball of the CSP is Sn-3.0Ag-0.5Cu. The CSPs were reflow-soldered on the Cu pad of the FR-4 PCB using Sn-8Zn-3Bi solder paste in air. The surface finish on the Cu pad was Ni-P(5 μm)/Au(0.05 μm), Ni-P(5 μm)/Au(0.5 μm), or heat-resistant pre-flux (Fig. 2). The Ni-P layer was formed by electroless plating and the Au layer was formed by substitution plating. Figure 3 schematically illustrates thermal process for reflow-soldering. The reflow profile was composed of preheat at 403~423 K for 60 s, followed by 20 s at a temperature above

CSP specification

- Size : 8.97mm×8.97mm
- Number of balls : 240
- Pitch : 0.5mm
- Ball composition : Sn3Ag0.5Cu
- Ball diameter : $\phi 0.32\text{mm}$
- Ball height : 0.29mm

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Fig. 1 Structure and specification of CSP used in this work.

Fig. 2 Structure of PCB pad plating.

Fig. 3 Reflow thermal profile.

Table 1 summary of testing condition.

Sample name	Solder ball	Solder paste	Reflow peak temperature	PCB pad plating
Sample A	Sn3Ag0.5Cu	Sn8Zn3Bi	483 K	Cu preflux
Sample B			483 K	Ni/Au(0.05 μm)
Sample C			503 K	
Sample D			483 K	Ni/Au(0.5 μm)
Sample E			503 K	

the melting point of the Sn-8Zn-3Bi solder. Peak temperatures varied between 483 K and 503 K. Table 1 summarizes the experimental testing conditions used in the study.

After reflow, the soldered specimens were either examined or subjected to an aging treatment. The aging treatment was carried out at 398 K for 1.8 Ms, 3.6 Ms and 5.4 Ms. After the reflow and aging treatment, microstructural observation of the solder joint was carried out. The soldered specimens were cut along the cross section, ground with emery paper, and polished with 1.0 μm diamond paste. The microstructure of the solder joints were observed using scanning electron microscopy (SEM). An electron-probe micro-analyzer (EPMA) was then used to determine the elemental composition of each phase formed at the bonded interface. To observe the microstructure of the bonded interface and to determine elemental composition in more detail, transmission electron microscopy (TEM) with an energy dispersion X-ray analyzer (EDX) was used. Thin foil specimen for TEM observation was prepared using focused ion beam (FIB) processing method.

The reliability of the CSP solder joints was evaluated through a cyclic bending test. Figure 4 Schematically illustrates the procedure. The test was carried out with a bending displacement of 1 mm and bending rate of 1.67 mm/s. All electrodes of the CSP were connected serially and the rupture life cycle was defined as the number of cycle at which disconnection of the circuit occurred.

Fig. 4 Schematic illustration of cyclic bending test procedure.

The effect of reflow peak temperature on the microstructure of the solder joint and interfacial bonding strength was more closely investigated using the following experiment. A Sn-3.0Ag-0.5Cu solder ball of 700 μm diameter was reflow-soldered onto a Cu pad plated with Ni(5 μm)/Au(0.05 μm) using the Sn-8Zn-3Bi solder paste. In this experiment, reflow peak temperature was varied from 483 to 513 K. Also, the joint strength was measured through a hot bump pull test. The procedure used for the hot bump pull test is shown in Fig. 5. The hot bump pull test was carried out at strain rate of 0.3 mm/s. Microstructural observation was carried out in the same way as described above.

3. Results and Discussion

3.1 Reliability of the CSP joint

Figure 6 presents the results of the cyclic bending test. Although the CSP joint without Ni-P/Au plating on the Cu

Fig. 5 Schematic illustration of hot bump pull test procedure.

Fig. 6 Result of cyclic bending test. Error bars shows maximum and minimum values.

pad (Sample A) had good rupture life, it was deteriorated readily during the aging treatment. Compared with Sample A, although the CSP joints on Ni-P/Au(0.05 μm) plated Cu pad with reflow peak temperatures of 483 K (Sample B) had somewhat shorter rupture life than Sample A in the as-soldered condition, it was improved after aging. The CSP joints on Ni-P/Au(0.05 μm) plated Cu pad with reflow a peak temperature of 503 K (Sample C) showed the longest rupture life of all the samples in the as-soldered condition although a slight deterioration of the joint reliability was found with a increase of holding time. On the other hand, the CSP joint on the Ni-P/Au (0.5 μm) plated Cu pad with reflow peak

temperatures of 483 K and 503 K had extremely short rupture life both in the as-soldered condition and after thermal exposure. From these result, it is concluded that Ni/Au plating on Cu pad with thin Au thickness is essential for long-term-reliability of the CSP soldered joint using the Sn-8Zn-3Bi solder.

3.2 Microstructural observation of the solder joint

The microstructure at the bonded interface of Sample A is shown in Fig. 7. An interfacial reaction layer was observed at the interface between the Cu pad and the solder in the as-soldered condition. Because Cu and Zn were detected by EPMA quantitative analysis in this layer, a Cu-Zn intermetallic compound (IMC) formed as the interfacial reaction products. However the exact composition of the IMC could not be determined because the layer was too thin for accurate EPMA analysis. Suganuma *et. al* reported that the Cu-Zn layer formed at the Cu/Sn-Zn solder interface was composed of Cu_5Zn_8 and CuZn .³⁾ Therefore it is likely that the IMC layer consists of Cu_5Zn_8 and/or CuZn . The microstructure at the bonded interface of Sample A after aging at 398 K is shown in Fig. 6(a). Growth of the interfacial reaction layer was observed. In addition, the phenomenon that Sn erode the Cu pad to form Cu-Sn IMC was observed.³⁾ The microstructure at the bonded interface of Sample B is shown in Fig. 8. A continuous flat interfacial reaction layer was observed at the interface between the Ni-P plating and the

a) as-reflowed condition

b) after aging at 398K for 5.4Ms.

Fig. 7 BE images at the bonded interface of sample A.

a) sample B

b) sample C

Fig. 8 BE images at the bonded interface of sample B and C.

Fig. 9 TEM micrograph at the bonded interface of sample B and diffraction pattern taken from interfacial reaction region.

solder in as-soldered condition. Because Au and Zn were detected by EPMA quantitative analysis in this layer, this reaction product is thought to be IMC composed of Au and Zn. On the other hand, in the joint subjected to higher reflow peak temperature (Sample C) as shown in Fig. 8, IMC including Au and Zn was found to be dispersed in the solder near the bonded interface and its morphology changed into particle-like, and another interfacial reaction layer consisting of Ni, Sn, Cu and Zn was formed at the solder/Ni-P plating interface. However, because the interfacial reaction layers in samples B and C were very thin, the chemical composition or phases could not be exactly determined by EPMA analysis, TEM observation for sample B and C was carried out. TEM micrograph and diffraction pattern taken from the bonded interfacial region of sample B are shown in Fig. 9. From TEM observation and EDX quantitative analysis, the reaction layer was identified as single phase of AuZn_3 . In the contrast, as shown in Fig. 10, a Au-Zn IMC layer formed at the bonded interface of sample C that was much thinner than sample B, and the reaction layer consisting of Ni, Sn, Cu, and Zn formed between the Au-Zn IMC layer and the solder. This reaction layer is determined as Ni_3Sn_4 type crystal structure, based on analysis of the diffraction pattern. And also Cu and Zn which are contained in this reaction layer considered to be dissolved in the Ni_3Sn_4 lattice. From these results, we can speculate that the reaction process between Ni/Au plating and Sn-8Zn-3Bi solder is as follows: When peak temperature is low (483 K), Zn in the molten solder, which is known as reactive element, react rapidly with Au plating to form a continuous layer of AuZn_3 . As the reflow peak temperature increase, the AuZn_3 layer dissolves into the molten solder to become thin, and simultaneously Ni-Sn-Cu-Zn IMC layer is formed by interdiffusion of the Ni and solder constituents.

Furthermore, the P-rich layer was observed adjacent to the

Fig. 10 TEM micrograph at the bonded interface of sample C and diffraction pattern taken from Ni-Sn-Cu-Zn layer.

interfacial reaction layer (Fig. 10). It is thought that this layer was formed by the consumption of Ni in the Ni-P plating during the interfacial reaction with the solder.⁴⁾ However, the thickness of the P-rich layer was approximately 30 nm, which is much thinner than the joints with Sn-Ag family solders.⁵⁾ Considering that the P-rich layer was not detected in sample B, it is thought that the Au-Zn layer, which forms during the reflow process, acts as a diffusion barrier that prevents Ni from excessively reacting with the solder. From these results, it is clear that the peak temperatures of reflow soldering considerably influence the interfacial reaction process.

Figure 11 shows the microstructure of the bonded interface of sample D. A interfacial reaction layer with thickness of about $2\mu\text{m}$ formed between the solder and Ni-P plating. Based on EPMA quantitative analysis, the layer was found to consist of Au and Zn. It is therefore likely that this layer was an Au-Zn IMC layer. Similarly, thick Au-Zn IMC layer was formed in sample E (Fig. 11). However, this layer formed in the solder layer apart from the bonded interface. This suggests that the layer was formed by the dissolution and diffusion of the Au-Zn layer into the solder during the reflow process at a higher peak temperature.

3.3 Relationship between joint reliability and microstructure of solder joint

To investigate the effect of the microstructure of the solder joints on joint reliability, crack paths in the cyclic bending test were observed. In sample A, the crack propagated in the solder layer in as-soldered condition (Fig. 12). This suggests that the joint of sample A in as-soldered condition had sufficient bonding strength between the solder and the Cu

Fig. 11 BE images at the bonded interface of sample D and E.

Fig. 12 Crack path of sample A in cyclic bending test in as soldered condition and after aging at 398 K for 5.4 Ms.

Fig. 13 Crack path of sample B in cyclic bending test in as soldered condition and after aging at 398 K for 5.4 Ms.

pads. However, after aging, thick Cu-Zn IMC layer and the Cu-Sn IMC formed between the Cu-Zn IMC/Cu pad interface was the crack propagation path or the crack initiation site (Fig. 12). From this result, it is concluded that the deterioration of joint reliability by aging was caused by the growth of the Cu-Zn IMC layer and the formation of the Cu-Sn IMC.

In sample B, the crack propagated along the Ni-P plating/Au-Zn IMC layer interface in as-soldered condition (Fig. 13). This suggests the bonding strength of this interface is insufficient in as the soldered condition. Although a Au-Zn IMC layer forms at Ni-P plating/solder interface as a result of Zn reacting with Au at an early stage of the reaction-process, further reaction of the solder and Ni-P plating may have been suppressed by the barrier effect of the Au-Zn IMC layer at the

lower reflow peak temperature. This may have lead to insufficient bonding strength of the interface. This hypothesis is supported by the fact that the rupture life cycle of sample B was improved after aging. In contrast, in sample C, the crack propagated in the solder layer both in the as-soldered condition and also after aging. Thus in sample C, higher bonding strength of the solder/Ni-P plating interface was obtained by the interfacial reaction between Ni-P plating and solder than was obtained for the sample B. It is known that when brittle P rich layer is formed in Ni-P plating adjacent to Sn-Ag type solder, the joint strength deteriorates.⁵⁻⁷⁾ However the P-rich layer of sample C was found to be 30 nm in thickness, which is significantly less than in Sn-Ag solders, we think that this very low thickness could not affect the joint reliability. This is caused by the barrier effect of the Au-Zn

Fig. 14 Crack path of sample C in cyclic bending test in as soldered condition and after aging at 398 K for 5.4Ms.

Fig. 15 Crack path of sample D and E in cyclic bending test in as soldered condition and after aging at 398 K for 5.4Ms.

IMC layer. From the results obtained for samples B and C, we consider that the moderate interfacial microstructure for joint reliability is complex structure consisting of the Ni-Sn-Cu-Zn layer and Au-Zn layer than the continuous flat Au-Zn IMC layer for avoiding initial fracture after soldering because the former interfacial structure had significantly higher interfacial strength in as-soldered condition. Therefore it is necessary to increase the reflow peak temperature to obtain the moderate interfacial structure.

In samples D and E, the crack was found to propagate along the thick Au-Zn layer/Ni-P plating interface (Fig. 15) and the joints showed extremely short rupture life both in as-soldered condition and after aging. This was caused by a defect formed at the bonded interface. Figure 16 shows the microstructure at the bonded interface of sample D. A delamination between the Au-Zn IMC layer and Ni plating was observed. This delamination may have formed because of the mismatch of coefficients of thermal expansion between the Ni-P plating and Au-Zn IMC layer. Therefore, it seems that the defect at the bonded interface existing before the cyclic bending test leads to extremely short rupture life of the joints of samples D and E.

3.4 Detail investigation on the effect of reflow peak temperature

Based on the results from the previous section, it is clear that reflow peak temperatures can considerably affect interfacial microstructure and joint reliability. To investigate this effect in more detail, bonding strength of the solder joints was measured directly by means of the solder bump pull test with varying reflow peak temperature. Figure 17 shows the

Fig. 16 SE image at the bonded interface of sample D.

Fig. 17 Result of hot bump pull test for the joint on Ni/Au(0.05 μm) plated Cu pad. Error bars shows maximum and minimum values.

Fig. 18 BE images at bonded interface of the joint on Ni-P/Au(0.05 μm) plated Cu pad with various peak temperatures.

joint strength of the samples with Ni/Au (0.05 μm) plating plotted as a function of reflow peak temperature. The joint strength was found to increase with reflow peak temperature up to 498 K and thereafter remained at a constant value. Figure 18 shows the effect of reflow peak temperature on the interfacial microstructure. When reflow peak temperature of 483 K was applied (Fig. 18(a)), the Au-Zn layer formed as continuous morphology at the bonded interface. When reflow peak temperature of 498 K was applied, the Au-Zn layer reduced in uniformity and Ni-Sn-Cu-Zn layer formed at the bonded interface. Finally, when reflow peak temperature of 513 K was applied, the Au-Zn layer completely disappeared at bonded interface. These results indicate that the Au-Zn IMC layer forms at the early stage of reflow-process, and dissolves and diffuses into the molten solder during subsequent heating. Since the joint strength increased with reflow peak temperature up to 498 K, we suggest that the optimum reflow peak temperature for the CSP assembly using Sn-8Zn-3Bi solder paste is found to be 498 K considering the advantage of low reflow temperature in the Sn-8Zn-3Bi solder.

4. Conclusions

In this work, we investigated the effect of several Cu pad plating materials and reflow peak temperatures on the reliability of the CSP joint with Sn-3.0Ag-0.5Cu solder ball using Sn-8Zn-3Bi solder paste. The main results are as follows.

- (1) After aging thick Cu-Zn IMC layer and Cu-Sn IMC formed at the bonded interface of the CSP joint without Ni-P/Au plating using Sn-8Zn-3Bi. This lead to the deterioration of the reliability of the joint. This suggests Ni-P/Au plating on Cu pad is needed for the long-term joint reliability.
- (2) For samples with a thin Au layer (0.05 μm) on Cu pad, Au-Zn IMC layer formed at the Ni-P plating/solder interface. Au-Zn IMC layer formed at the early stage of reflow-process

dissolved and diffused into the molten solder during subsequent heating. During this process, the interfacial reaction layer consisting of Ni, Sn, Cu and Zn formed simultaneously. This complex interfacial microstructure consisting of Ni-Sn-Cu-Zn layer and Au-Zn layer had higher bonding strength between the Ni-P plating and the solder than the flat Au-Zn layer was found to have improved joint reliability.

When thick Au layer (0.5 μm) plated on the Cu pad, joint reliability was greatly reduced, because a delamination defect was formed at the Ni-P plating/Au-Zn IMC layer interface. So the thickness of Au plating should be as thin as possible within a processing limitation of Au plating.

(3) Reflow peak temperature can have a strong influence on interfacial microstructure and joint strength. To obtain higher joint strength by the formation of the moderate interfacial microstructure, reflow peak temperature must be accurately controlled.

(4) Our study has shown that the combination of 0.05 μm thick Au plating and reflow peak temperature of 498 K are optimum conditions for joint reliability.

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