Interfacial Reactions of High-Bi Alloys on Various Substrates

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Bi-Sn alloys with high Bi concentration are potential candidates to replace high-Pb alloys as high-temperature Pb-free solders. Interfacial reactions between high-Bi alloys (Sn concentration 2 wt.%, 5 wt.%, and 10 wt.%) and various substrates have been investigated to understand the intermetallic compound formation and interfacial morphological evolution at the joint interface. The substrates investigated include Ni, Au/Ni, Cu, and Ag/Cu layers deposited on Si chips. The interfacial reactions were carried out at 300°C and 120°C to simulate the liquid/solid and solid/solid reactions, respectively, at such solder joints. Experimental results reveal that the intermetallic compound formation and interfacial morphological evolution vary with the substrate and the Sn concentration of the Bi-Sn alloy.

Key words: Interfacial reaction, high-temperature solder, Bi, substrate

INTRODUCTION

Pb-Sn alloys with Pb concentration higher than 95 wt.% possess higher melting points around 312°C to 327°C and can withstand multiple reflows in the packaging process, and so have long been used as high-temperature solders in high-end electronic packaging.^{1,2} Interfacial reactions accompanying intermetallic compound formation usually occur in solder joints during reflow and are taken as an indicator that joining of the solder joint is complete.^{3–6} However, excessive growth and irregular morphological evolution of intermetallic compounds may degrade the solder joint mechanically.⁷ Therefore, clear understanding of interfacial reactions is crucial for reliability evaluation of solder joints.

To address the global trend for bans on Pb in microelectronic products, efforts have been made to search for high-temperature Pb-free alloys to replace high-Pb solders. Eutectic Bi-Ag alloy (Bi-2.5 wt.%Ag) is attractive because of its acceptable melting point (262.5°C) and affordable cost.⁸ Increasing the Ag content to 11 wt.% can improve the thermal conductivity and electrical resistivity of Bi-Ag alloy for higher application performance.^{9,10}

It was found that no intermetallic compound was formed at the Bi-Ag/Cu interface after reflowing at 350°C. Instead, grain boundary grooving of the Cu substrate by liquid Bi-Ag penetration occurred, which provided mechanical bonding between the solder and substrate.⁸ By contrast, two intermetallic compounds, namely cellular-type NiBi₃ and layer-type NiBi, were formed at the Bi-Ag/Ni interface.⁸ Zn-xSn alloys ($x = 20$ wt.%, 30 wt.%, and 40 wt.%) are also potential candidate high-temperature solders. Two intermetallic compounds, i.e., CuZn₅ and Cu₅Zn₈, were formed at the Zn-xSn/Cu interface after soldering.¹¹ Mechanical tests indicated that the shear strength of the Zn-xSn/Cu joint was higher than that for Pb-5 wt.%Sn. It was also found that the thermal conductivity of the Zn-xSn alloys was higher than that of Pb-5 wt.%Sn. For the Zn-xSn/Ni ($x = 20$ wt.%, 30 wt.%, 40 wt.%, and 50 wt.%) interfacial reactions at 380°C to 420°C, only one intermetallic compound, namely Ni₅Zn₂₁, was formed at the interface.¹² However, the growth behavior and microstructure of the Ni₅Zn₂₁ phase varied with the Sn content.

Bi-Sn alloys with high Bi content are other potential substitutes for high-Pb alloys. High-Bi alloy has a wide mushy zone, with liquidus temperature around 250°C but solidus temperature of

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Fig. 1. Cross-sectional SEM micrographs of (a) Ni substrate deposited with an Au layer and (b) Cu substrate deposited with an Ag layer.

only 138°C.¹³ During soldering, the limited Sn in the high-Bi alloy is consumed quickly due to intermetallic compound formation, and accordingly the solidus temperature increases rapidly, enabling high-Bi alloys to withstand subsequent multiple reflows. When high-Bi alloys (Sn ≤ 10 wt.%) were soldered with Cu, only the Cu₃Sn phase was formed at the interface when reacted at 300°C for 15 s to 90 min.¹⁴ The Cu₃Sn phase was found to detach from the Cu substrate, and the gap between the Cu₃Sn phase and the Cu substrate was filled by a (Bi) phase. Shear testing indicated that the high-Bi/Cu joint was mechanically comparable to the high-Pb/Cu joint. To gain more information regarding the compatibility of high-Bi alloys with other substrates, the interfacial reactions between high-Bi alloys and other common substrates were investigated in this work. The common substrates investigated include Ni, Au/Ni, and Ag/Cu.

EXPERIMENTAL PROCEDURES

Sn (99.9% purity; Showa, Japan) and Bi (99.998%; Alfa Aesar, USA) shots were used to prepare high-Bi alloys. Proper amounts of Sn and Bi shots were weighed and sealed in a vacuum quartz tube (4×10^{-3} torr). The sealed vacuum quartz tube was

Fig. 2. SEM micrographs of Bi-2 wt.%Sn/Ni interfaces reacted at 300°C for (a) 15 s, (b) 90 s, (c) 10 min, and (d) 90 min.

Fig. 3. SEM micrographs of Bi-5 wt.%Sn/Ni interfaces reacted at 300°C for (a) 15 s, (b) 90 s, (c) 10 min, and (d) 90 min.

Fig. 4. SEM micrographs of Bi-10 wt.%Sn/Ni interfaces reacted at 300°C for (a) 15 s, (b) 90 s, (c) 10 min, and (d) 90 min.

Fig. 5. SEM micrographs of high-Bi/Ni interfaces reacted at 120°C: (a) Bi-2 wt.%Sn/Ni for 120 h, (b) Bi-2 wt.%Sn/Ni for 2400 h, (c) Bi-5 wt.%Sn/Ni for 120 h, (d) Bi-5 wt.%Sn/Ni for 2400 h, (e) Bi-10 wt.%Sn/Ni for 120 h, and (f) Bi-10 wt.%Sn/Ni for 2400 h.

put into a furnace at 900°C, and the quartz tube was shaken periodically to enhance the homogeneity of the molten alloys during annealing. After 120 h, the molten alloy was quenched in ice–water. Several pieces (2.2 mg) of alloy were cut from the solidified ingot and were cleaned in H₂SO₄ (5%) solution for 3 s to remove surface oxides and contamination.

Four types of metallic layers, i.e., Ni, Au/Ni, Cu, and Ag/Cu, were deposited on Si chips as substrates. The first type of substrate was a 400-μm-thick Si chip (4 inch diameter) with a 25-μm-thick Ni layer deposited by electroplating at 0.6 A for 3 h. Prior to Ni electroplating, a 0.4-μm-thick Ni layer was sputtered onto the Si chip to improve the adhesion between the subsequent electroplated Ni layer and the Si. The second type of substrate was fabricated

by depositing a thin Au layer on the first type of substrate using electroless plating. Electroless plating was conducted at 75°C to 85°C, and the time was controlled to 15 min, which produced a thin Au layer of about 0.7 μm, as shown in Fig. 1a. The third type of substrate was a 400-μm-thick Si chip with a deposited Cu layer. A 0.4-μm-thick Cu layer was first deposited on the Si chip using sputtering and was thickened to 25 μm using electroplating at 0.05 A for 3 h. A 2.5-μm-thick Ag layer was grown on the electroplated Cu layer using electroplating as the fourth type of substrate, as shown in Fig. 1b. Ag electroplating was carried out at 0.1 A for 3.5 min. To control the joining area between the high-Bi alloy and the substrate, a solder mask with an open square window was coated on the substrate. The

Fig. 6. Relationship between the thickness of Ni_3Sn_4 formed at the high-Bi/Ni interface reacted at $120^\circ C$ and the square root of reaction time. $\blacktriangle$ Bi-10 wt.%Sn, $\blacksquare$ Bi-5 wt.%Sn, $\bullet$ Bi-2 wt.%Sn.

side length of the open square window was $600\ \mu m$. An alloy piece was coated with flux (Magana 51 flux, USA) and then placed on the uncovered surface of the substrate.

Two types of experiments were conducted to investigate the interfacial reactions of the high-Bi alloys on the various substrates. One was liquid/solid reaction with reaction temperature of $300^\circ C$, at which the high-Bi alloys were in liquid state. The other was solid/solid reaction at $120^\circ C$, at which the high-Bi alloys were in solid state. In the former reaction, the samples were placed on a hot plate set at $300^\circ C$. The high-Bi alloys melted rapidly and wetted the substrate. After reaction for 15 s to 90 min, the samples were removed from the hot plate and were mounted in epoxy resin for metallographic examination. The samples were ground and polished to expose cross-sections of the joint interface. Scanning electron microscopy (SEM) was used to observe the microstructure of the joint interface. Energy-dispersive x-ray (EDX) spectrometry was used for compositional analysis of the reaction products. For the solid/solid reaction, the samples were placed on a hot plate at $300^\circ C$ for 90 s to accomplish joining between the high-Bi alloy and substrate. Then, the samples were placed in an oven at $120^\circ C$ for various lengths of time. After reaction, the high-Bi/substrate interfaces were examined metallographically as described above.

RESULTS AND DISCUSSION

High-Bi/Ni Interfacial Reactions

Figure 2 shows SEM micrographs of Bi-2 wt.%Sn/Ni interfaces reacted at $300^\circ C$ for 15 s to 90 min. No noticeable intermetallic compound was found at the interface after reaction for 15 s, as seen in Fig. 2a. A new phase layer was formed at the interface after 90 s, as seen in Fig. 2b, although it was too thin (less than $0.5\ \mu m$) to conduct compositional analysis using SEM-EDX. After reaction for 10 min, as seen in Fig. 2c, an island-type phase was found at the

Fig. 7. SEM micrographs of Bi-2 wt.%Sn/Au/Ni interfaces reacted at $300^\circ C$ for (a) 15 s, (b) 90 s, and (c) 10 min.

interface. Compositional analysis indicated that this phase contained 56.2 at.%Ni-42.5 at.%Sn-1.3 at.%Bi, identified as the Ni_3Sn_2 phase. After reaction for 90 min, another new phase layer was found at the Ni_3Sn_2 /Ni interface, as seen in Fig. 2d. According to the result of compositional analysis (49.2 at.%Ni-46.7 at.%Bi-4.1 at.%Sn), this new phase was identified as the NiBi phase with a small amount of dissolved Sn.

When the Sn content was increased to 5 wt.%, intermetallic compound was hardly formed until 10 min of reaction, as seen in Fig. 3c. The intermetallic

Fig. 8. SEM micrographs of Bi-2 wt.%Sn/Au/Ni interfaces reacted at 120°C for (a) 120 h and (b) 720 h.

compound grew thicker to about 4.3 μm after 90 min, as seen in Fig. 3d, and it was identified as the Ni_3Sn_4 phase according to the result of compositional analysis (43.7 at.%Ni-56.3 at.%Sn). On increasing the Sn content to 10 wt.%, the amount of gray needle-type Sn-rich phase in the solder also increased, as seen in Fig. 4. The intermetallic compound grew to about 4.8 μm after 90 min, as seen in Fig. 4d, and it was also identified as the Ni_3Sn_4 phase. Based on the above results, the type of intermetallic compound formed at the liquid/solid high-Bi alloy/Ni interface varied with the Sn content. When the Sn content was only 2 wt.%, the Sn supply was limited and the Ni-rich Ni_3Sn_2 phase was formed, as seen in Fig. 2. After longer reaction (90 min), the Sn might be exhausted at the interface and Bi started to react with Ni to form the NiBi phase there. By contrast, when the Sn content was higher than 5 wt.%, the Sn-rich Ni_3Sn_4 phase was formed at the interface due to sufficient Sn supply.

Figure 5 shows high-Bi/Ni interfaces reacted at 120°C for 120 h and 2400 h, for Sn content in the high-Bi alloy of 2 wt.%, 5 wt.%, and 10 wt.%. It was found that only one intermetallic compound was formed at the interface, being identified as the Ni_3Sn_4 phase. The Ni_3Sn_4 phase grew very slowly. After reaction for 2400 h, the thickness of the Ni_3Sn_4 phase was only 2.2 μm , 3.1 μm , and 3.8 μm

for Sn content of 2 wt.%, 5 wt.%, and 10 wt.%, respectively. Figure 6 shows the relationship between the Ni_3Sn_4 thickness and the square root of reaction time. It was found that the growth of the Ni_3Sn_4 phase followed a parabolic law, indicating a diffusion-controlled mechanism. As discussed above, the Ni-rich Ni_3Sn_2 phase instead of the Sn-rich Ni_3Sn_4 phase was formed at the Bi-2 wt.%Sn/Ni interface reacted at 300°C due to limited Sn supply. However, the Sn-rich Ni_3Sn_4 phase could be formed at 120°C even though the Sn content of the Bi-Sn alloy was only 2 wt.%. The absence of the Ni_3Sn_2 phase at the Bi-2 wt.%Sn/Ni interface reacted at 120°C was attributed to the fact that the Ni_3Sn_2 phase was hardly observed at lower reaction temperatures.^{15–17} Nucleation difficulty of the Ni_3Sn_2 phase at lower reaction temperatures is likely to be the cause.¹⁵ Instead, Sn atoms gradually accumulated at the interface, and the Ni_3Sn_4 phase was formed as the Sn supply was sufficient for Ni_3Sn_4 phase formation. Because the Sn atoms accumulated at the interface by solid-state diffusion, a slow growth rate of the Ni_3Sn_4 phase was observed as mentioned above.

High-Bi/Ni Interfacial Reactions with an Inserted Au Layer

Figure 7 shows SEM micrographs of Bi-2 wt.%Sn/Au/Ni interfaces reacted at 300°C for 15 s to 10 min. Similar to the Bi-2 wt.%Sn/Ni interface shown in Fig. 2, the intermetallic compound was still very thin after 90 s of reaction, as seen in Fig. 7b. After 10 min of reaction, the intermetallic compound grew thicker and exhibited an island-type structure, as seen in Fig. 7c. Compositional analysis by EDX revealed that the intermetallic compound contained 56.4 at.%Ni-39.4 at.%Sn-4.2 at.%Au, being identified as the Ni_3Sn_2 phase with minor dissolved Au. No Au layer was present at the interface, indicating that the Au layer had dissolved into the molten Bi-Sn alloy during the liquid/solid reaction and was immediately incorporated into the formation of the Ni_3Sn_2 phase. Comparison of Figs. 2 and 7 reveals that insertion of a 0.7- μm -thick Au layer had a negligible influence on the high-Bi/Ni interfacial reaction. Figure 8 shows Bi-2 wt.%Sn/Au/Ni interfaces reacted at 120°C for 120 h and 720 h. Similar to Fig. 5, only the Ni_3Sn_4 phase was formed at the interface after the solid-state reaction.

High-Bi/Cu Interfacial Reactions

In our previous study,¹⁴ we investigated liquid/solid high-Bi/Cu interfacial reactions at 300°C, for Sn concentrations in the high-Bi alloy of 2 wt.%, 5 wt.%, and 10 wt.%. Only the Cu_3Sn phase was formed at the interface, and it detached from the underlying Cu substrate rapidly. The gap between the detached Cu_3Sn phase and the Cu substrate was filled with a (Bi) phase layer. In the present study, we continued to investigate the high-Bi/Cu

Fig. 9. SEM micrographs of Bi-2 wt.%Sn/Cu interfaces: (a) as fabricated, and after reaction at 120°C for (b) 120 h, (c) 360 h, and (d) 2400 h.

interfacial reaction at a lower temperature of 120°C, i.e., the solid/solid reaction. The samples used for solid/solid reaction were fabricated by joining the Bi-Sn alloys with the Cu substrates at 300°C for 90 s.

Figure 9 shows SEM micrographs of Bi-2 wt.%Sn/Cu interfaces reacted at 120°C for various lengths of time. At the as-fabricated Bi-2 wt.%Sn/Cu interface, shown in Fig. 9a, the Cu_3Sn phase detached from the Cu substrate and a (Bi) phase layer was filled in between the Cu_3Sn phase and the Cu. After solid/solid reaction, as seen in Fig. 9b–d, two significant changes were observed at the interface and are worthy of discussion. One was the phase transformation from Cu_3Sn to Cu_6Sn_5 with increasing reaction time. The other was that the (Bi) phase layer gradually disappeared and the intermetallic compound reattached to the Cu substrate. Similar results were found for two other systems, i.e., Bi-5 wt.%Sn/Cu and Bi-10 wt.%Sn/Cu, as shown in Figs. 10 and 11. From Fig. 10, we can further understand the mechanism of reattachment of intermetallic compound. In Fig. 10b, most of the Cu_3Sn phase had reattached to the Cu substrate, while at some local regions the Cu_3Sn phase was not directly attached to the Cu substrate but was separated by a (Bi) phase layer. It was found that a new Cu_3Sn phase layer, denoted as Cu_3Sn (lower),

formed along the (Bi)/Cu interface. To verify the existence of the lower Cu_3Sn phase, the reaction time was reduced to 72 h; the corresponding cross-sectional SEM image of the sample is shown in Fig. 12. In Fig. 12, the (Bi) phase layer is located in between two Cu_3Sn phase layers. The upper Cu_3Sn phase layer was formed by liquid/solid reaction at 300°C, corresponding to the case shown in Fig. 10a, while the lower Cu_3Sn phase layer was formed by solid/solid reaction at 120°C. According to the results of compositional analysis, the (Bi) phase layer in Fig. 10a contained 96.9 at.%Bi-2.0 at.%Sn-1.1 at.%Cu. During the solid/solid reaction, the Sn content in the (Bi) phase layer was consumed by reaction with Cu to form the Cu_3Sn phase at the (Bi)/Cu interface, i.e., the lower Cu_3Sn phase layer in Fig. 10b. Upon increasing the reaction time to 360 h, two Cu_3Sn phase layers were simultaneously transformed into the Cu_6Sn_5 phase, as seen in Fig. 10c. This was due to sufficient Sn supply from the Bi-Sn alloy after longer solid/solid reaction. In addition, the upper and lower Cu_6Sn_5 phase layers mostly contacted with each other, except at some local regions where more Bi atoms aggregated. Because the growth of the lower Cu_6Sn_5 phase reduced the space for the (Bi) phase layer, most of the Bi atoms were forced to aggregate laterally to some local regions. This local accumulation of Bi

Fig. 10. SEM micrographs of Bi-5 wt.%Sn/Cu interfaces: (a) as fabricated, and after reaction at 120°C for (b) 120 h, (c) 360 h, and (d) 2400 h.

Fig. 11. SEM micrographs of Bi-10 wt.%Sn/Cu interfaces: (a) as fabricated, and after reaction at 120°C for (b) 120 h, (c) 360 h, and (d) 2400 h.

Fig. 12. SEM micrograph of Bi-5 wt.%Sn/Cu interface reacted at 120°C for 72 h.

Fig. 13. SEM micrographs of Bi-2 wt.%Sn/Cu interfaces after multiple reactions: (a) liquid/solid + solid/solid + liquid/solid and (b) liquid/solid + solid/solid + liquid/solid + solid/solid. The conditions of the liquid/solid and solid/solid reactions are 300°C for 90 s and 120°C for 360 h, respectively.

atoms caused the upper Cu_6Sn_5 phase layer to bend upward to release the compressive stress, forming an interesting “ Cu_6Sn_5 bridging” microstructure, as seen in Fig. 10c. After reaction for 2400 h, the Cu_6Sn_5 phase was firmly attached to the Cu substrate and no (Bi) phase was found, as shown in Fig. 10d. A new Cu_3Sn phase began to form at the Cu_6Sn_5 /Cu interface. Because the Cu_6Sn_5 and

Fig. 14. SEM micrographs of Bi-2 wt.%Sn/Ag/Cu interfaces reacted at 300°C for (a) 15 s, (b) 90 s, and (c) 90 min.

Cu_3Sn phases contained negligible Bi, the disappearance of the (Bi) phase layer indicates that most of the Bi atoms returned to the Bi-Sn alloy. However, one question then arises: How did the Bi atoms return to the alloy in the condition that the upper Cu_6Sn_5 phase layer acted as a barrier? The real mechanism is still unknown, but a possible one is that the Bi atoms returned to the alloy by way of grain boundaries in the upper Cu_6Sn_5 phase layer.

Fig. 15. SEM micrograph of a Bi-2 wt.%Sn/Ag/Cu interface reacted at 120°C for 360 h.

It was also found that, the higher the Sn concentration, the faster the reattachment of the intermetallic compound to the Cu substrate and the phase transformation. In the Bi-10 wt.%Sn/Cu system shown in Fig. 11b, the Cu_3Sn phase was transformed into the Cu_6Sn_5 phase after 120 h. Simultaneously, the Cu_6Sn_5 phase had firmly reattached to the Cu substrate and no (Bi) phase existed between the Cu_6Sn_5 phase and the Cu substrate.

Figure 13 shows SEM micrographs of Bi-2 wt.%Sn/Cu interfaces after multiple reactions. The reaction condition of the sample shown in Fig. 13a was similar to that in Fig. 9c but with an additional liquid/solid reaction at 300°C for 90 s. In Fig. 9c, the Cu_6Sn_5 phase had mostly reattached to the Cu substrate after the solid/solid reaction. However, after the additional liquid/solid reaction, the Cu_6Sn_5 phase was transformed into the Cu_3Sn phase and detached from the Cu substrate again, as seen in Fig. 13a. The (Bi) phase layer was once again formed in between the detached Cu_3Sn phase and the Cu substrate. Apparently, the Bi atoms in the molten state had high mobility and were able to diffuse through the Cu_3Sn phase layer by way of grain boundaries (or triple junctions) and accumulated at the $\text{Cu}_3\text{Sn}/\text{Cu}$ interface to form a continuous (Bi) phase layer. The surface layer of the Cu substrate was partially dissolved by the molten (Bi) phase, and it looked like the Cu_3Sn phase detached from the Cu substrate. When the sample in Fig. 13a was further annealed at 120°C for 360 h, the Cu_3Sn phase was transformed into the Cu_6Sn_5 phase again and mostly reattached to the Cu substrate, except at some local (Bi)-accumulated regions, as seen in Fig. 13b. This microstructural evolution is similar to that in Fig. 9c. It appeared that the microstructural evolution of the high-Bi/Cu interface correlated strongly with the reaction condition.

High-Bi/Cu Interfacial Reactions with an Inserted Ag Layer

Figure 14 shows SEM micrographs of Bi-2 wt.%Sn/Ag/Cu interfaces reacted at 300°C for 15 s to 90 min.

Similar to our previous results on the Bi-2 wt.%Sn/Cu interfacial reaction,¹⁴ only the Cu_3Sn phase was formed at the interface, detaching from the underlying Cu substrate rapidly. The gap between the detached Cu_3Sn phase and the Cu substrate was filled with a (Bi) phase layer. No Ag was observed at the interface. According to the results of compositional analysis, the Cu_3Sn and (Bi) phase contained 1.3 at.% and 1.6 at.% Ag, respectively, indicating that the Ag layer had been consumed and dissolved in the Cu_3Sn and (Bi) phase during the liquid/solid reaction. Figure 15 shows a Bi-2 wt.%Sn/Ag/Cu interface reacted at 120°C for 360 h. Similar to Fig. 9c, the Cu_3Sn phase had been transformed into the Cu_6Sn_5 phase and reattached to the Cu substrate.

CONCLUSIONS

Interfacial reactions between Bi- x wt.%Sn ($x = 2, 5$, and 10) alloys and various substrates (Ni, Au/Ni, Cu, and Ag/Cu) were investigated, including liquid/solid reaction at 300°C and solid/solid reaction at 120°C. In the Bi- x wt.%Sn/Ni interfacial reactions at 300°C, the type of intermetallic compound formed strongly depended upon the Sn concentration. When the Sn concentration was only 2 wt.%, the Ni-rich Ni_3Sn_2 phase was formed due to limited Sn supply. After longer reaction, Bi started to react with Ni to form the NiBi phase at the $\text{Ni}_3\text{Sn}_2/\text{Ni}$ interface. When the Sn concentration was higher than 5 wt.%, only the Sn-rich Ni_3Sn_4 phase was found. In the Bi- x wt.%Sn/Ni interfacial reactions at 120°C, only the Ni_3Sn_4 phase was found regardless of the Sn concentration. The absence of the Ni_3Sn_2 phase at the Bi-2 wt.%Sn/Ni interface was ascribed to its nucleation difficulty at lower reaction temperatures. The interfacial reactions between Bi- x wt.%Sn alloy and Au/Ni behaved similarly to the Bi- x wt.%Sn/Ni system.

In the Bi- x wt.%Sn/Cu interfacial reactions, only the Cu_3Sn phase was formed at the interface after joining, and it detached from the Cu substrate. The gap between the detached Cu_3Sn phase and the Cu substrate was filled by a (Bi) phase layer. After solid/solid reaction at 120°C, the Cu_3Sn phase was gradually transformed into the Cu_6Sn_5 phase and reattached back to the Cu substrate, accompanied by disappearance of the (Bi) phase layer. The rates of phase transformation and interfacial morphological evolution were faster for higher Sn concentration in the Bi-Sn alloy. Insertion of an Ag layer on the Cu substrate had a negligible effect on the interfacial reactions.

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