Bi-Base Composite Solders for Mounting Power Semiconductor Devices

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Abstract

A novel Bi-base solder for mounting semiconductor power devices on inverters used in hybrid and fuel-cell vehicles was studied. The solder consists of Bi-base matrix (m.p. (melting point)=270°C), which facilitates high-temperature soldering, and dispersion particles of a Cu–Al–Mn alloy, whose thermoelastic martensitic microstructure is expected to relax the thermal stress. The tensile strength of the developed solders was found to be remarkably improved compared with that of pure Bi. Results of tensile tests at elevated temperatures showed greater elongation and lower strength than those at room temperature. However, sufficient tensile strength was still remained at 195°C. Effects of the CTE (coefficient of thermal expansion) and the surface substance of chips and substrates on the IMC (intermetallic compound) formation and thermal cycling properties were investigated. Even after 1983 thermal cycles between –40°C and 200°C, neither intermetallic compounds nor cracks were observed at the Cu/Bi-base solder interfaces in the CTE matched samples.

Keywords: Bi-Base Composite Solder, CuAlMn Powder, Mechanical Property, IMC (intermetallic compound), Thermal Cycling Test

1. Introduction

In the next generation semiconductor power devices, high current density and high voltage I (the electric current)–V (voltage source) properties as well as heat resistance are required. However, conventional Si has a temperature limitation of 150°C, which is not sufficient for future applications. On the other hand, for compound semiconductor power devices, such as GaN and SiC are applicable to high-temperature operations beyond 200°C.[1, 2] Consequently, exposure of power devices to severe thermal stress caused by the expanded temperature hysteresis between –40°C and above 200°C, which are assumed to occur in the cold winter weather and in full-powered engine rooms, respectively, is problematic.

As well as high-temperature power devices, high-temperature solders applicable above 250°C are indispensable for the inter-connection in electronic packaging. However, only harmful substances, such as Pb (m.p.=327°C), Cd (321°C) and Tl (303°C), and expensive alloys, such as

Au–20mass%Sn (280°C), Au–3.5mass%Si (363°C) and Au–12.5mass%Ge (361°C), have appropriate melting points for high temperature use. If their ductility and weak strength could be improved, Bi and its alloys (271°C) would be exceptional candidates for high-temperature solders with not only suitable melting point but also reasonable cost. To overcome such problems, our group has proposed the use of in-situ composite solders of Bi–Cu–Sb, Bi–Cu–Sn and Bi–Cu–Zn ternary alloys produced by rapid quenching processes such as gas atomizing and melt spinning methods.[3] Their microstructure consists of Bi-base matrix (270°C) which facilitates high-temperature soldering, and fine dispersion particles of Cu–X IMCs, which bring about strengthening of the solder itself. However, not only strength but also thermal stress resistance are simultaneously required in solder materials.

The bcc- β phase in Cu–Al–Mn alloys exhibits thermoelastic martensitic transformation which can be con-

trolled by composition, heat treatment and applied stress.[4–7] This martensitic phase shows extensive ductility, which is expected to relax the thermal stress when martensitic particles are dispersed in the Bi solder matrix. Fortunately, Cu-base alloys are immiscible with the Bi matrix, which means that the desirable properties of martensitic particles would not be dissipated. In the present study, the fabrication process of martensitic particle reinforced Bi base solders, the microstructural characteristics and mechanical properties of the composite solders, and the thermal cycle properties of the joined assemblies were investigated.

2. Experimental Procedure

2.1 Fabrication of the composite solder

Martensitic powder of a Cu–23Al–2Mn (at.%) alloy was prepared by a gasatomizing method. It is difficult to mix Cu-base powder with a Bi melt because the wettability of Cu by a Bi melt is quite poor. To solve this problem, electroless nickel was plated onto the surface of each particle using the two types of solution listed in Table 1.[8] Then, the Ni-coated powder was mixed with a Bi melt at 500°C for 5 min in a quartz tube encapsulated with decompressed Ar gas. During the mixing process, not only Cu-base particles but also Bi₃Ni precipitates, which formed by a reaction between the Ni coating and Bi, were homogeneously dispersed in the Bi melt. As a result, the obtained composite solder consisted of 60% Bi, 30% Cu–23Al–2Mn particles and 10% Bi₃Ni precipitates in volume fraction.

2.2 Microstructure and mechanical properties

The microstructure and composition were examined by an OM (optical microscope) and EPMA (electron probe micro analyzer: JEOL JXA-8100). The transformation temperature was determined by DSC (differential scanning calorimetry: Netzsch DSC-404) referring to heating curves. The measurements were carried out in an argon gas flow, with heating and cooling rates of 5°C/min, using sintered Al₂O₃ crucibles.

Tensile test specimens were prepared from cast ingots (10mmφ×60mm) of composite solders and pure Bi. Stress–strain properties were measured by a tensile test at a strain rate of 10^{−3}/s at temperatures of −40°C, 25°C, 105°C and 195°C.

The coefficient of thermal expansion (CTE) was measured by a dilatometer (Netzsch TASC 414/3) in the temperature range between −40°C and 200°C with heating and cooling at rates of 5°C/min.

Table 1. The bath composition for electroless coating Ni on Cu–Al–Mn powder by dropping method. [8]

The complexing	
Cu–Al–Mn powder	20 g
Sodium citrate	4 g
Distilled water	200 cc
The solution of metallic salt in water	
Nickel sulfate	44.8 g
Distilled water	240 cc
The solution of reducer in water	
Sodium hypophosphite	45.2 g
Sodium hydrate	17 g
Distilled water	240 cc

Fig. 1. Illustration of a jointed sample.

2.3 Thermal cycling test

Figure 1 shows a schematic illustration of a jointed sample of a Ni-plated semiconductor chip (IGBT: Si/Ni) or its imitation (CIC: laminated Cu/FeNi/Cu plate), and a solder and substrate (CIC or DBA) which were stacked and soldered on a hot plate in a glove box filled with Ar gas. Details of each element are shown in Table 2.

Thermal cycling tests were carried out on the jointed assemblies in air. Microstructure evolution and occurrence of voids, cracks and fractures were examined in the cross sections of treated samples and the reliability of solder joints were evaluated.

3. Results and Discussion

3.1 Microstructure of composite solder

The as-cast microstructure of a composite solder is shown in Fig. 2(a). It can be seen that the Cu–Al–Mn particles and Bi₃Ni precipitates are homogeneously dispersed in the Bi matrix. According to the EPMA measurement, the composition of the particles remained Cu–23Al–2Mn (at.%) and martensitic morphology was confirmed as shown in Fig. 2(b).

The melting temperature of the composite solder was determined from the heating curve of a DSC profile as

Table 2. Sample properties for thermal cycling test, chip, substrate and solder.

(a) Chip	Structure	CTE ($10^{-6}/^{\circ}\text{C}$)	Thickness of interface layer (μm)	
CIC	Cu/FeNi/ Cu	4	40	
IGBT	Si/ Ni	4	0.7	
(b) Substrate	Structure	CTE ($10^{-6}/^{\circ}\text{C}$)	Thickness of interface layer (μm)	
CIC	Cu/FeNi/ Cu	4	200	
Ni/CIC	Cu/FeNi/Cu/ Ni	4	50	
DBA	Ni/Al/AlN/Al/ Ni	4	5	
(c) Solder	m.p. ($^{\circ}\text{C}$)	CTE ($10^{-6}/^{\circ}\text{C}$)	Tensile strength (MPa)	Elongation (%)
Sn-0.7Cu	220	22	8	~ 20
Bi+CuAlMn	270	10–12	25	2

bold: interface layer

Fig. 2. (a) Cross sectional microstructure of the fabricated Bi(60%)–Cu–23Al–2Mn(30%)–Bi₃Ni(10%) solder observed by EPMA and (b) martensite state of Cu–23Al–2Mn(at.%) particle after the corrosion treatment observed by OM.

shown in Fig. 3. The first sharp peak, which appeared at 270°C corresponds to the melting temperature of the Bi matrix, and the second one represents decomposition of Bi₃Ni into BiNi and liquid phases. No peaks caused by martensitic transformation could be detected because the size and volume fraction of Cu–Al–Mn particles is quite small.

Fig. 3. DSC profile of the fabricated Bi(60%)–Cu–23Al–2Mn(30%)–Bi₃Ni(10%) solder.

Fig. 4. Stress and strain curve of Bi and Bi+CuAlMn solders at 25°C.

3.2 Mechanical properties

Figure 4 shows stress–strain curves of the composite solder and pure Bi specimens at room temperature. It can be seen that both the tensile strength and the elongation of composite solder are greater than those of pure Bi, which suggests that Cu–Al–Mn particles and Bi₃Ni precipitates improve the mechanical properties effectively.

The mechanical properties of the composite solder strongly depend on the testing temperature, as shown in

Fig. 5. Stress and strain curve of Bi+CuAlMn solders at -40°C , 25°C , 105°C and 195°C .

Fig. 6. CTE (coefficient of thermal expansion) curve of the fabricated Bi+CuAlMn solder.

Fig. 5. The elongation at -40°C and 25°C was only about 0.3% and 1.5%, respectively. On the contrary, more than 9% elongation could be obtained at 105°C and 195°C . Tensile strength remained at 13 MPa at 195°C , which is sufficient strain and strength for high temperature solders.

Figure 6 shows the CTE properties of the composite solder in a wide temperature range between -40°C and 200°C . At the heating and cooling measurements, the CTE varies from $9 \times 10^{-6}/^{\circ}\text{C}$ to $14 \times 10^{-6}/^{\circ}\text{C}$, which is almost the same CTE value as that of pure Bi ($13.4 \times 10^{-6}/^{\circ}\text{C}$). [9]

The CTE of the Sn base solder and Pb base high temperature solder exceeds $22 \times 10^{-6}/^{\circ}\text{C}$ and $29 \times 10^{-6}/^{\circ}\text{C}$, respectively, in the same temperature range. [9] On the other hand, the CTE of the semiconductor chip and the substrate for semiconductor devices, is about $4 \times 10^{-6}/^{\circ}\text{C}$, and 4 to $6 \times 10^{-6}/^{\circ}\text{C}$, [9, 10] respectively. The thermal stress based on the mismatch of CTE among the chip, solder and substrate certainly causes the formation of cracks, which results in fracture of the assembly, even though Sn and Pb exhibit relaxation due to their softness and larger fracture strain. However, the CTE value of the

Fig. 7. Cross sectional view of the jointed samples after thermal cycling test of $-40/200^{\circ}\text{C}$, (a) IGBT/Sn-0.7Cu/Ni/CIC at 1,513 cycles, (b) CIC/Bi+CuAlMn/CIC at 1,983 cycles, and (c) IGBT/Bi+CuAlMn/DBA at 1,944 cycles.

Bi base composite solders is smaller than that of conventional Sn- or Pb-base solders, which is expected to decrease the thermal stress.

3.3 Thermal cycling test

Figures 7(a), (b) and (c) show cross-sectional microstructures of IGBT/Sn-0.7Cu(Ni)CIC, CIC/Bi+CuAlMn/CIC and IGBT/Bi+CuAlMn/(Ni)DBA samples after 1,983

Fig. 8. Cross sectional view of the jointed samples after the thermal cycling test of $-40/250^{\circ}\text{C}$, 200 cycles, (a) CIC/Bi+CuAlMn/CIC and (b) IGBT/Sn-0.7Cu/DBA.

cycles of the $-40/200^{\circ}\text{C}$ thermal cycling test, respectively. It was found that IMC layers of Ni_3Sn_4 and Bi_3Ni formed between the Ni layer and the Sn base and Bi base solders, respectively, whose ductility causes the formation and growth of fatal cracks as shown in Figs. 7(a) and 7(c). Few cracks and no IMC phase were obtained in the Bi+CuAlMn composite solder soldered on Cu surfaces of the CIC plates as shown in Fig. 7(b). This indicates that (1) no IMC formation warrants the stable soldered interface, and (2) Cu–Al–Mn particles not only have a relaxation effect but also act as a barrier against the growth of cracks. It was also suggested that the CTE values of a chip and a substrate should be matched to avoid fracture due to severe thermal hysteresis. It can be concluded, therefore, that only the interface between the Cu layer and the Bi+CuAlMn composite solder which joined the CTE-matched chip and the substrate exhibited reliable solder joints even after almost 2,000 cycles of the $-40/200^{\circ}\text{C}$ thermal cycling test.

Furthermore, no cracks and IMC phases were observed after 200 cycles even at a wider temperature hysteresis between -40°C and 250°C , as shown in Fig. 8(a). On the other hand, the soldered joint using conventional Sn-0.7Cu solder melted and peeled off during the same test as shown in Fig. 8(b).

4. Conclusions

A new type of composite solder which consists of a Bi-base matrix and dispersion particles of a Cu–Al–Mn thermoelastic phase alloy was developed. The tensile strength of the developed solder is almost twice as high as pure Bi, while the elongation at elevated temperatures drastically increases up to 9.5% while retaining its tensile high strength. The dispersion particles with a

martensitic structure relax thermal stress due to temperature hysteresis and prevent cracks from extending in the Bi matrix. A reliable soldered interface which endures severe thermal cycles can be realized when the soldered chip and substrate have a Cu surface and similar CTE properties, which suggests that the developed composite solder is applicable for temperature hysteresis between -40°C and 200°C under appropriate soldering conditions.

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